Local Oscillators and Mass Sensors for IMPACT

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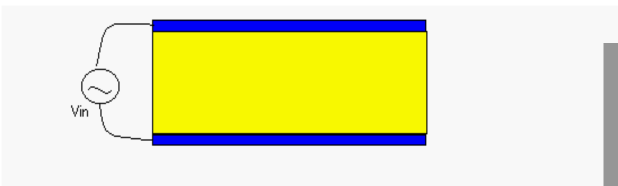
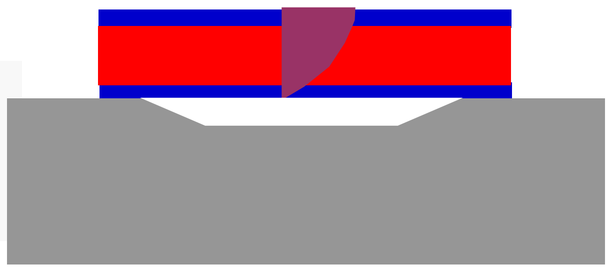
Film Bulk Acoustic Resonator (FBAR)

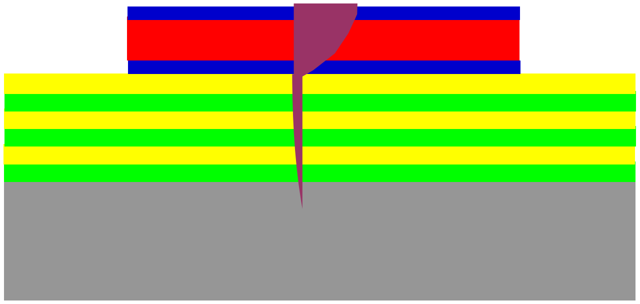
❑ Film bulk acoustic resonator (FBAR).

- Large acoustic impedance mismatch on both sides of piezoelectric film.





FBAR

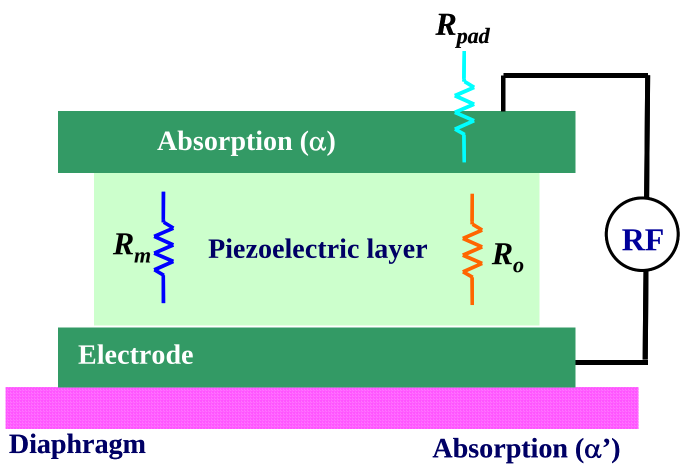


SMR

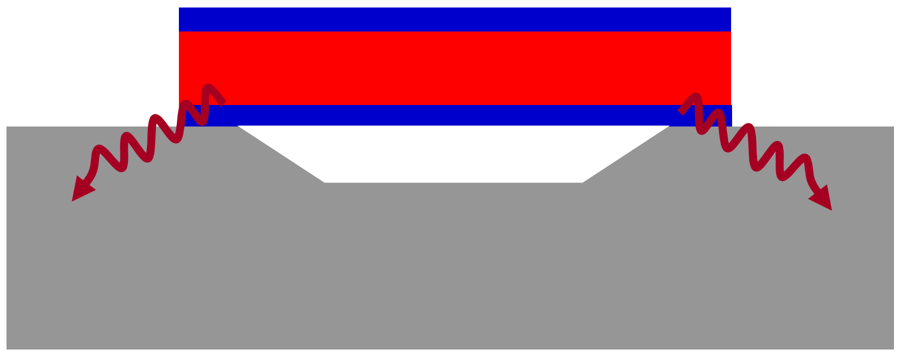
➢ *Impedance mismatch:*	Air	Bragg reflector (frequency dependent)
➢ *Energy confinement:*	Excellent	Shear wave propagates into substrate
➢ *Power handling:*	Good	Better (thermal flux through substrate)
➢ *Manufacturing:*	More masks	Multi-layers(>7): thickness control

Improving Q factor of FBAR

$$Q \equiv \frac{\omega \cdot (Stroed \;\; energy)}{Dissipated \;\; energy\,(per\ cycle)}$$



- **Acoustic energy loss**.
  - thickness excitation
  - in-plane lateral modes

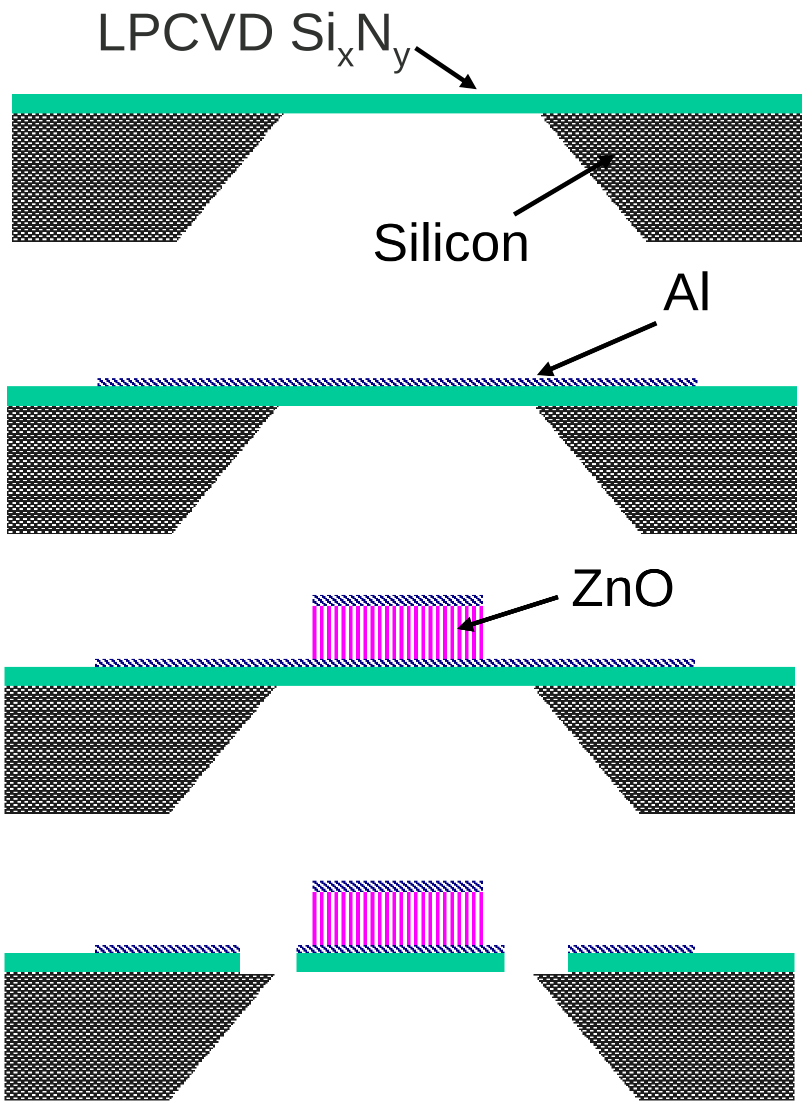


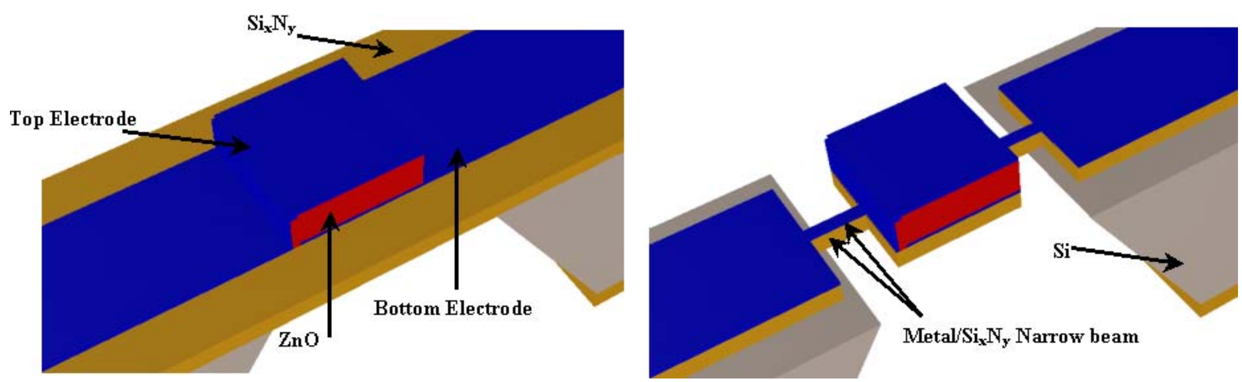
- Minimize lateral acoustic loss (lamb wave) through the supportting areas.

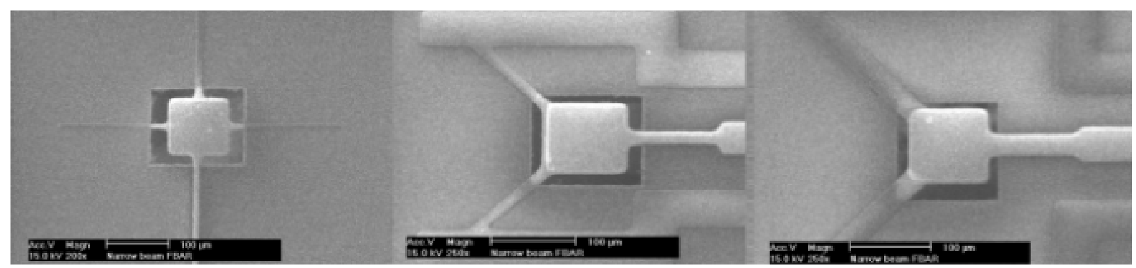
➔ Free standing structure

- **Dielectric loss: Q_p (ZnO vs. AlN)**
- **Ohmic loss (R_s) : Q_s**
  - Improve crystalline quality of piezoelectric film
  - Polish surface of ZnO or AlN.

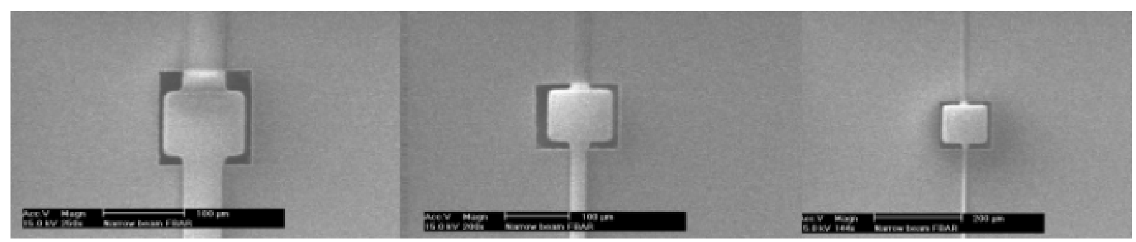
Narrow Beam Supported FBARs on Silicon





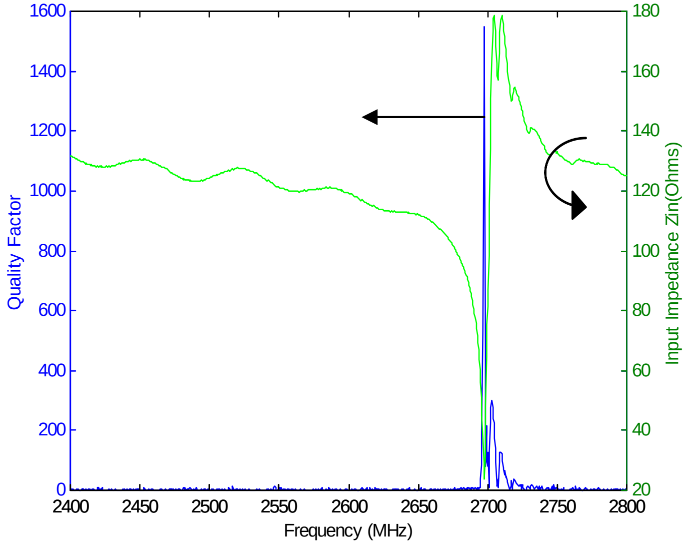


(a) (b) (c)

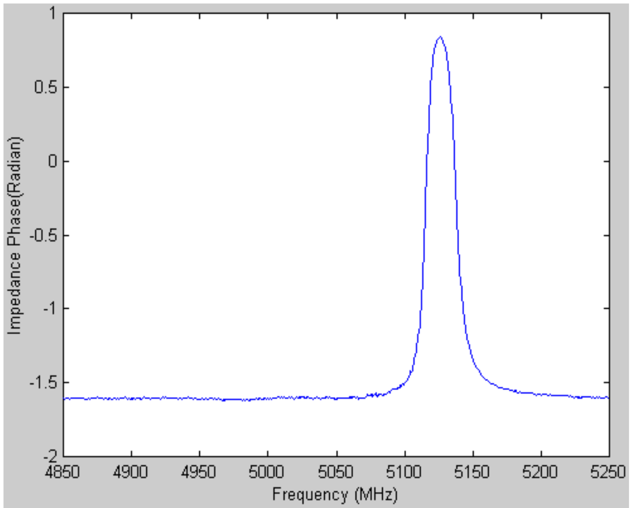


(d) (e) (f)

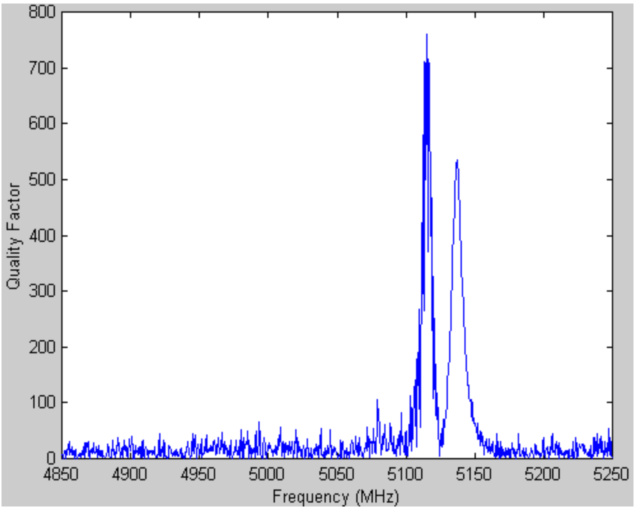
Experimental Results of Narrow Beam Supported FBARs at 2 and 5GHz



FBAR at 2GHz



Phase of FBAR impedance vs. frequency.



FBAR Q vs frequency.

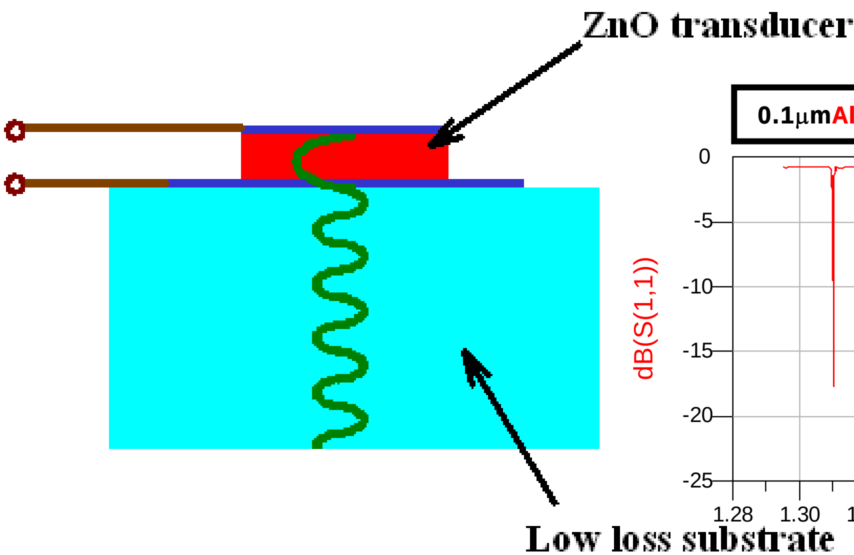
ZnO active area size (μm x μm)	100 x 100					
Beam width (μm)	10		25		50	
Number of beams	2	4	2	3	2	3
Q factor@ 5.1GHz excluding electrode series and contact resistances	**769**	649	605	580	525	517

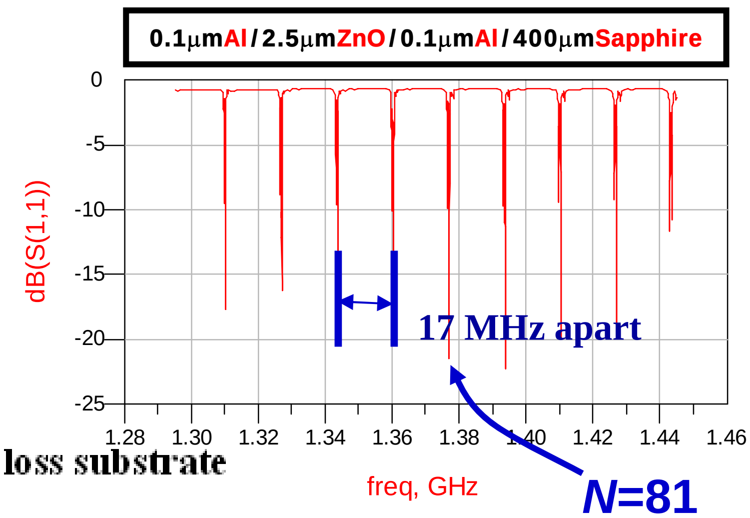
- **Free-standing, isolated FBAR**
  - **Higher Q with**
    - **narrower support beam**
    - **less number of support beams**

Bulk Acoustic Resonators

❑Film bulk acoustic resonator (FBAR).

- Large acoustic impedance mismatch on both sides of piezoelectric film





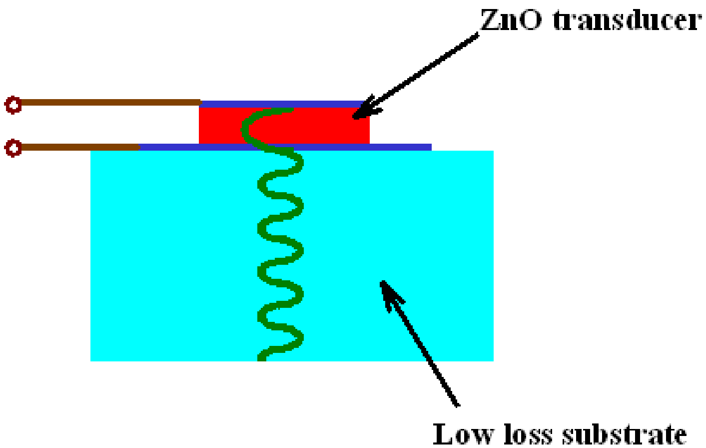
$$f_r \approx \frac{N}{2(\underbrace{d_{ZnO}/V_{ZnO}}_{\text{Highest f·Q Region}} + \underbrace{d_{substrate}/V_{substrate}}_{\text{Fundamental mode : \textasciitilde 17MHz}})^{-1}}$$

$V_{sapphire} \approx 11{,}100 m/s$, $d_{sapphire} \approx 400 \mu m$

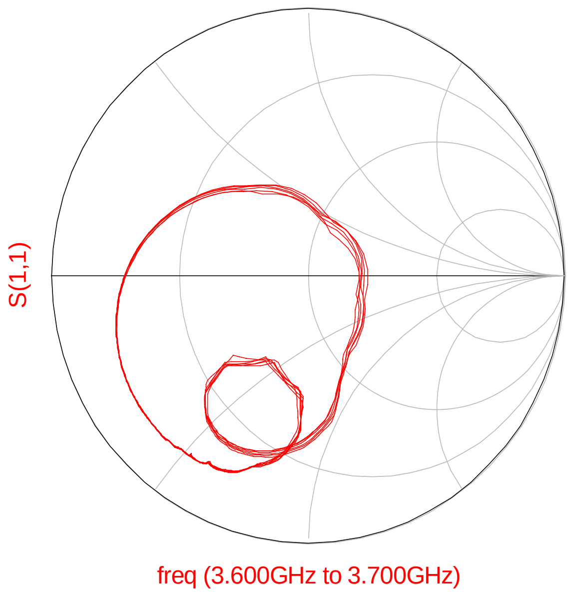
❑High-tone bulk acoustic resonator (HBAR).

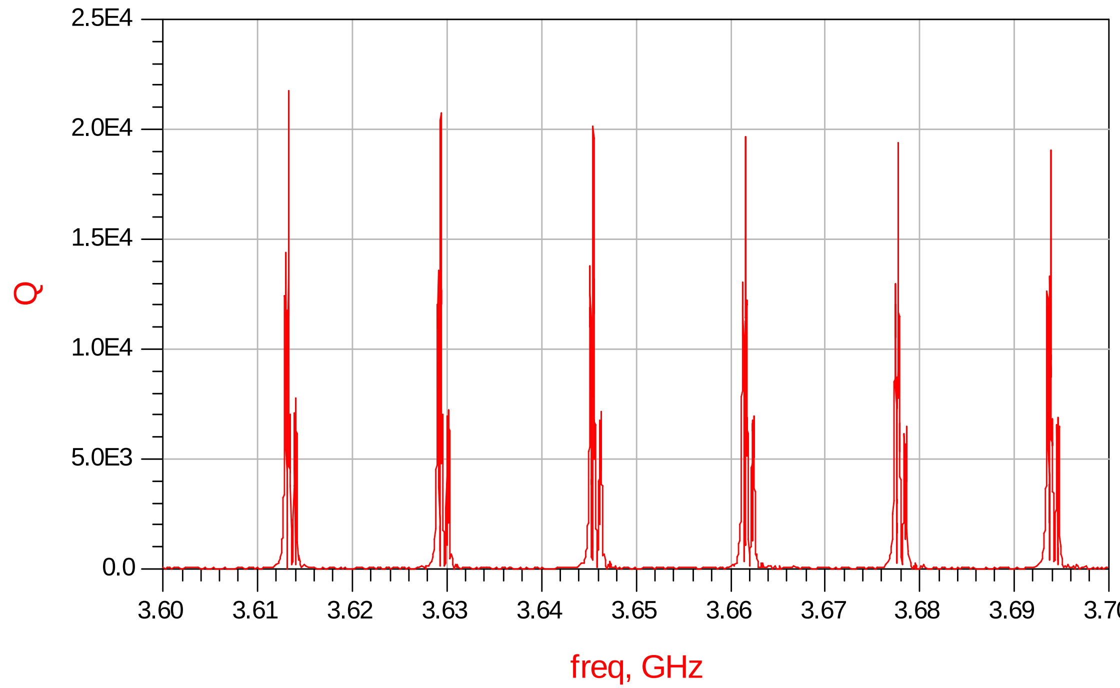
- Multiple resonances at an interval of tens of MHz.
- Extremely high Q with a low loss and double-side polished (~10Å) substrate.

Measured *3.6 GHz* HBAR Characteristics



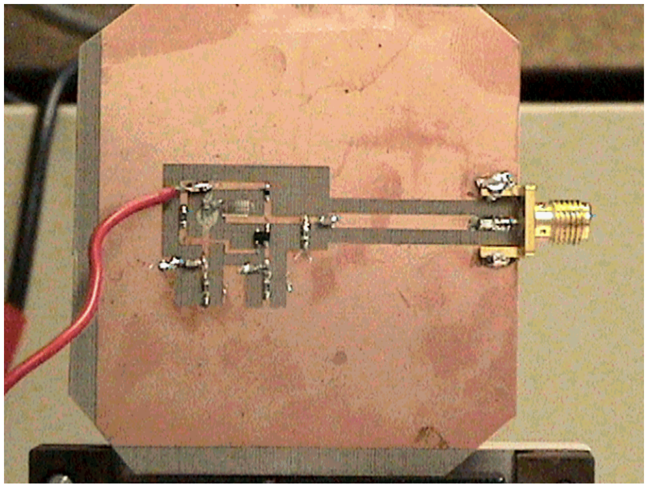
0.1μmAl / 1.0μmZnO / 0.1μmAl / 400μmSapphire



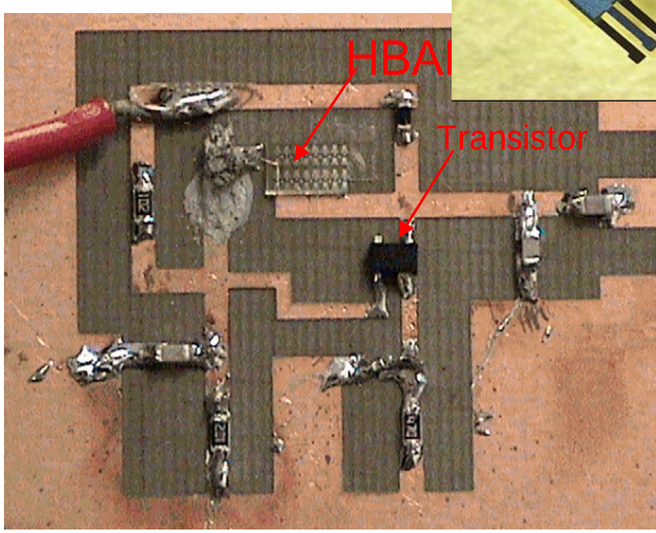


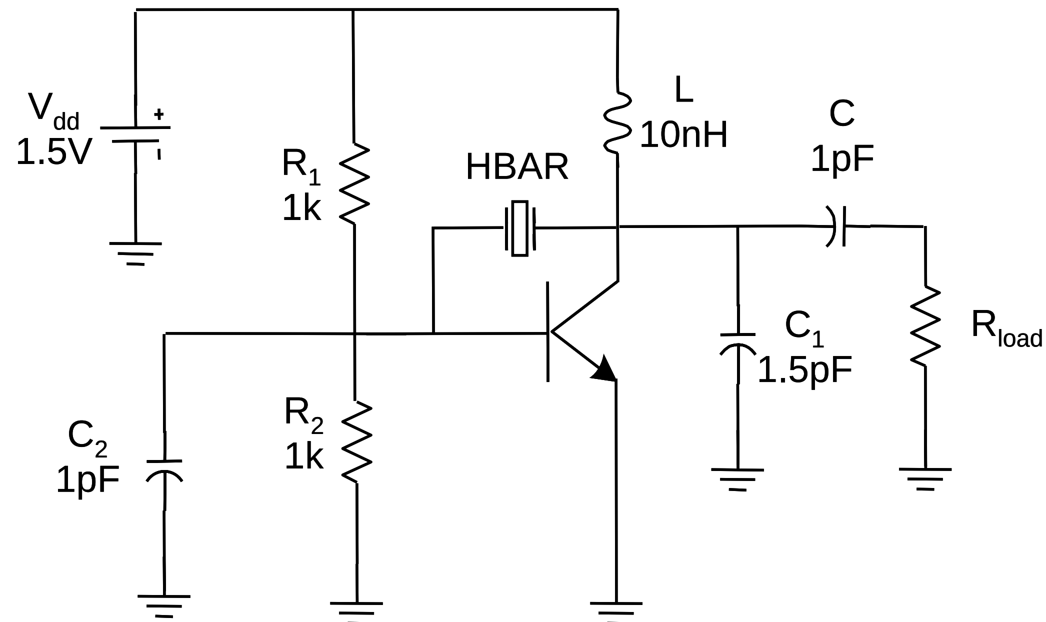
Q is around 19,000 at 3.677GHz

HBAR-Based 3.6 GHz Oscillator on PCB



HBAR's Q = 19,000 at 3.6 GHz

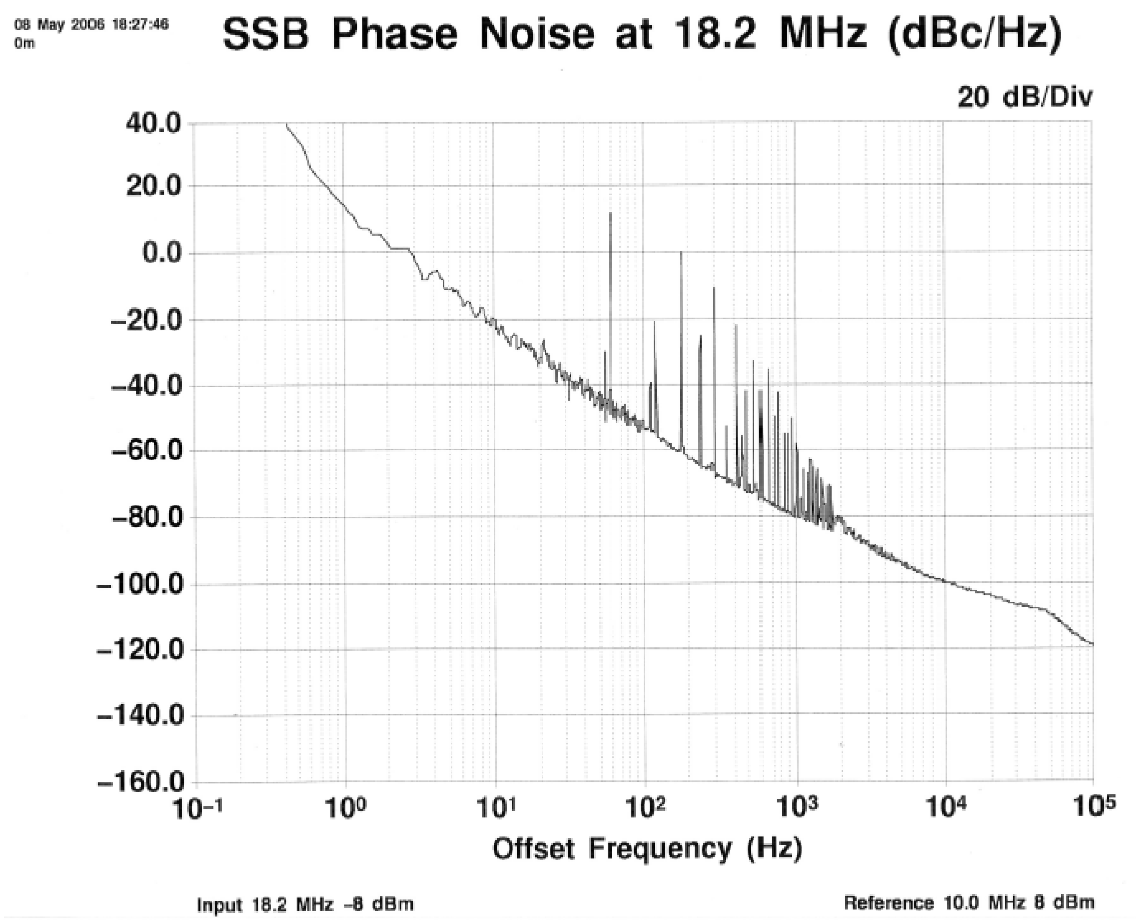




- Wire bonding on HBAR; epoxy used for one-side connection to PCB due to small area reserved on PCB.
- PCB not good looking due to many trials and errors (bypassing and replacing) during this first phase of the oscillator building.

Phase Noise of 3.6 GHz HBAR-Based Oscillator

- Alan Brannon of J. Kitching's Group at NIST measured the phase noise on a Timing Solutions TSC 5120A phase noise test set.

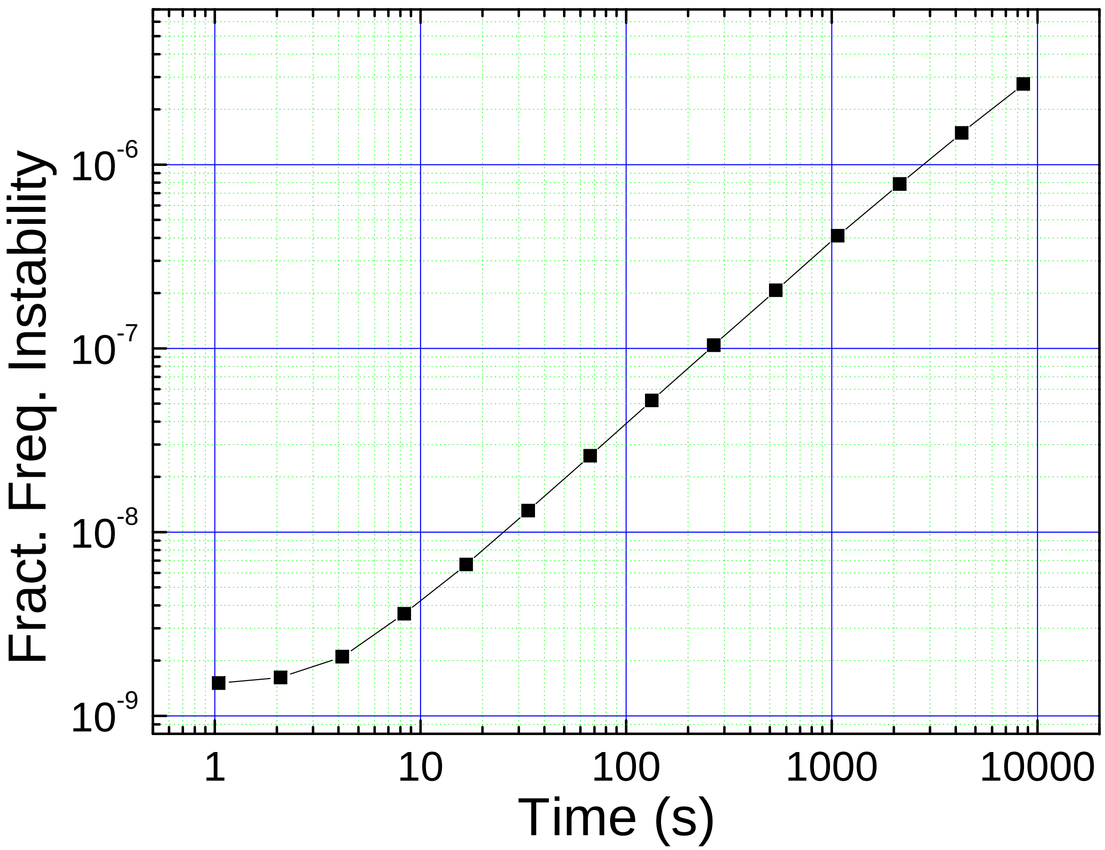


- Signal was down-converted to the required range of frequencies between 1MHz and 30MHz.
- Reference frequency was a frequency from a synthesizer that was externally referenced to a hydrogen maser ensemble.
- Additive mixer noise was low enough to make these measurements.

Phase noise: -102dBc/Hz at 10kHz offset **Power consumption: 3.2mW**

Measured Allan Deviation of HBAR-Based Pierce Oscillator

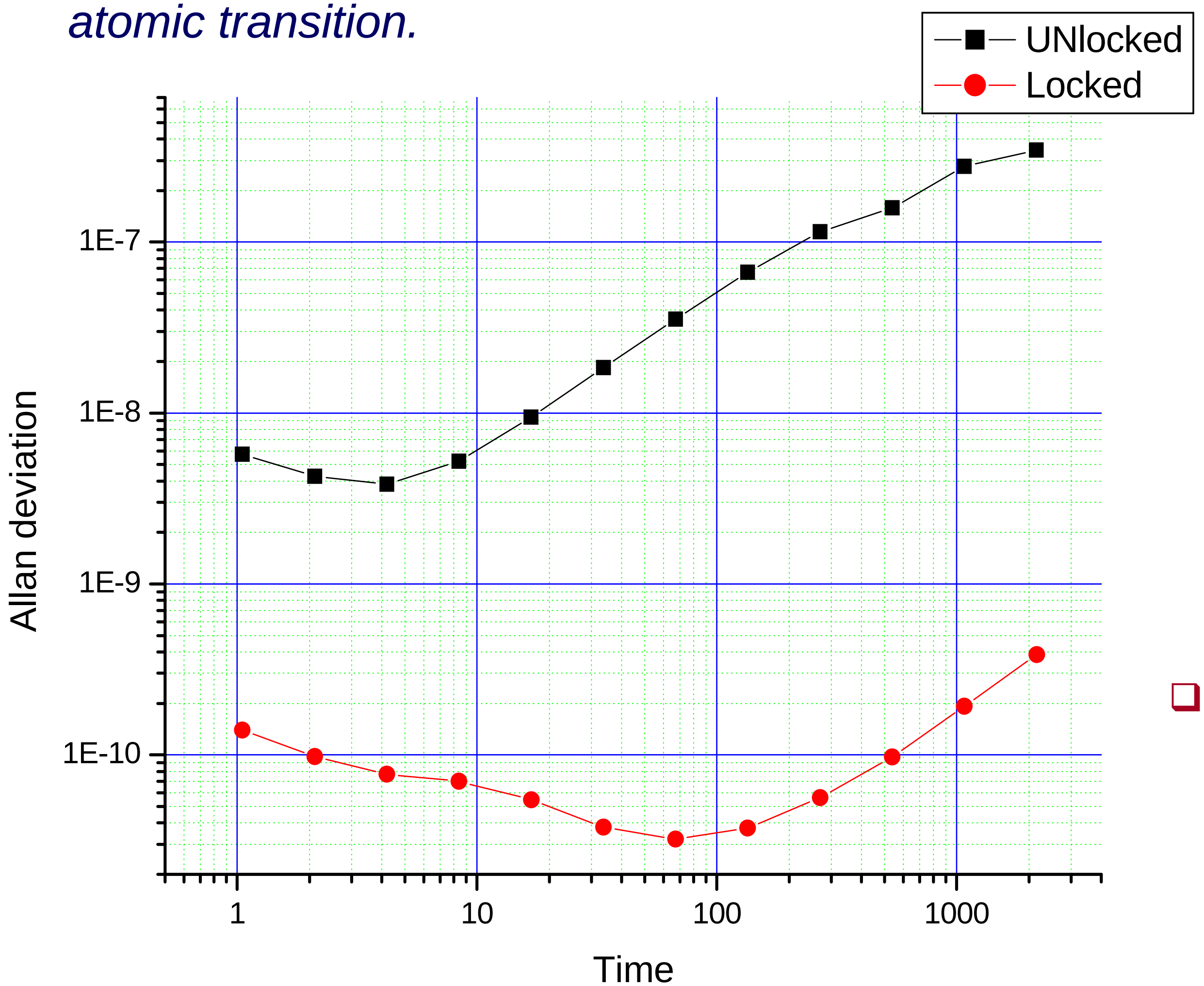
- Alan Brannon of J. Kitching's Group at NIST measured the Allan deviation.



Time(s)	*Allan deviation*
1.04	1.5×10^{-9}
2.08	1.6×10^{-9}
4.17	2.1×10^{-9}
8.35	3.6×10^{-9}
16.7	6.7×10^{-9}
33.4	1.3×10^{-8}
66.8	2.6×10^{-8}
133	5.2×10^{-8}
267	1.0×10^{-7}
534	2.1×10^{-7}
1068	4.1×10^{-7}
2137	7.9×10^{-7}

Measured Allan Deviations

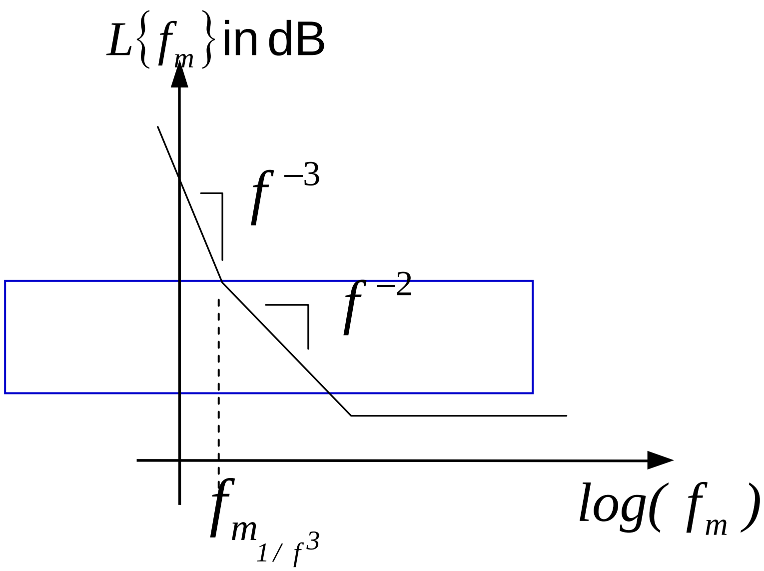
- The HBAR oscillator was locked up to NIST's table-top CPT physics assembly
  - by mixing it with a 200 MHz signal from a synthesizer to get the frequency near the atomic transition.



- Locked Allan deviation is $1.5x10^{-10}$ @ 1 sec

Modified Leeson's Equation for Phase Noise

$$L\{f_m\} = 10\log\left[\left\{1 + \frac{f_o^2}{(2f_mQ_{load})^2}\right\}\left\{1 + \frac{f_c}{f_m}\right\}\frac{Fk_BT}{2P_{s,av}} + \frac{2k_BTRK_o^2}{f_m^2}\right]$$



$$L\{f_m\} = f(Q_{load}, P_{s,av})$$

Design Parameters:
Q and signal power level

f_m: frequency offset from the center frequency

f_o: center frequency

f_c: flicker frequency

Q_{load}: loaded Q of the tuned circuit

F: noise factor (linear value for noise figure in dB scale)

k_BT: 4.1 x 10^{-21} at 300K

$P_{s,av}$: average power at oscillator

R: equivalent noise resistance of tuning diode

K_o: oscillator voltage gain

RF/Microwave Circuit Design for Wireless Application by U.L. Rohde and D.P. Newkirk, pp. 736 – 737.

Expected Phase Noise At 4.6 GHz

- *Measured* HBAR-based Oscillator's Phase Noise: -102dBc/Hz @ 10kHz offset
  - Center frequency (f_o): 3.68 GHz
  - HBAR's Q (Q_{load}): 19,000
  - Power consumption ($P_{s,av}$): 3.2 mW
- *Expected* HBAR-based Oscillator's Phase Noise: -95dBc/Hz @ 10kHz offset
  - Center frequency (f_o): 4.6 GHz
  - HBAR's Q (Q_{load}): 11,000 (based on the measured *fQ* product)
  - Power consumption ($P_{s,av}$): 3.2 mW

$$L\{f_m\} = 10\log\left[\left\{1+\frac{f_o^2}{\left(2f_mQ_{load}\right)^2}\right\}\left\{1+\frac{f_c}{f_m}\right\}\frac{Fk_BT}{2P_{s,av}} + \frac{2k_BTRK_o^2}{f_m^2}\right]$$

- *Hittite's* HMC429LP4's Phase Noise: -85dBc/Hz @ 10kHz offset
  - Center frequency (f_o): 4.45 – 5.0 GHz
  - Power consumption ($P_{s,av}$): 90 mW
- HBAR oscillator reduces the power consumption 30 times, yet still improves the phase noise by 10dBc/Hz, compared to a commercial VCO.

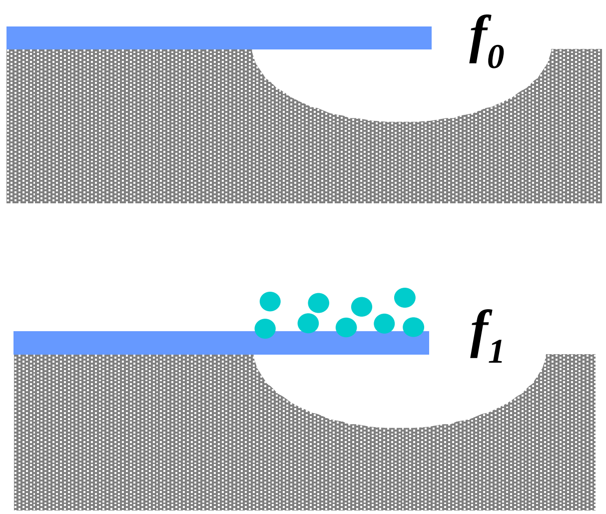
Expected Phase Noise At 9.19 GHz

- *Expected* HBAR-based Oscillator's Phase Noise: -79dBc/Hz @ 10kHz offset
  - Center frequency (f_o): 9.19 GHz
  - HBAR's Q (Q_{load}): 4,680 (based on the measured *fQ* product)
  - Power consumption ($P_{s,av}$): 3.2 mW
  - Noise factor F: about two times larger than that at 3.68 GHz

$$L\{f_m\} = 10\log\left[\left\{1+\frac{f_o^2}{(2f_mQ_{load})^2}\right\}\left\{1+\frac{f_c}{f_m}\right\}\frac{Fk_BT}{2P_{s,av}}+\frac{2k_BTRK_o^2}{f_m^2}\right]$$

Resonant Mass Sensors

- Output in frequency,monitored by electrical readout
- Inherent noise immunity, easy interface with digital systems
- Excellent minimum detectable mass, high sensitivity.



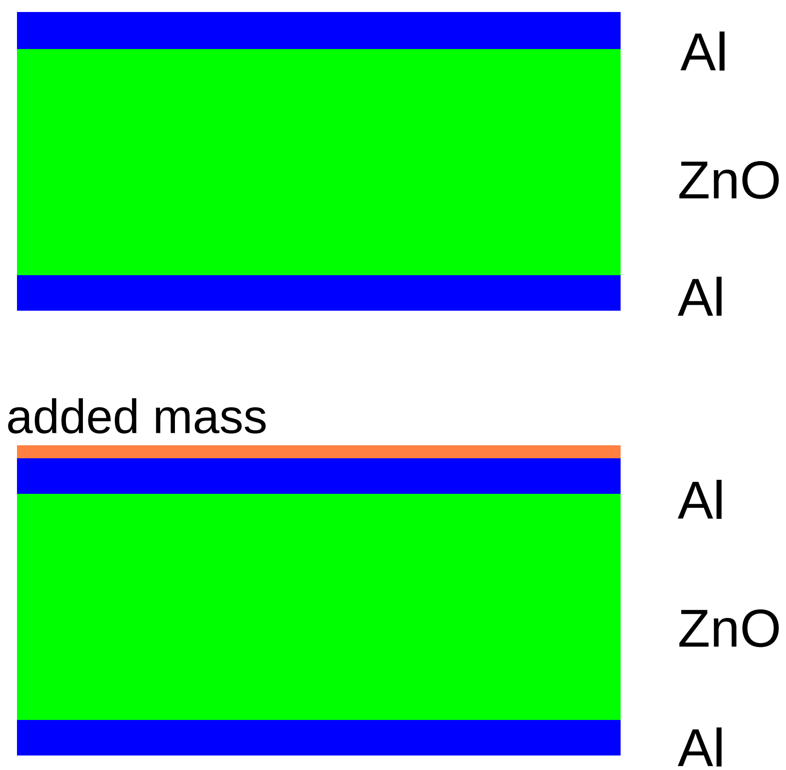
- Actuation:
  - Optical
  - Electrostatic
  - Magnetic
  - Piezoelectric
- Sensing:
  - Optical
  - Capacitive
  - Piezoresistive
  - Piezoelectric

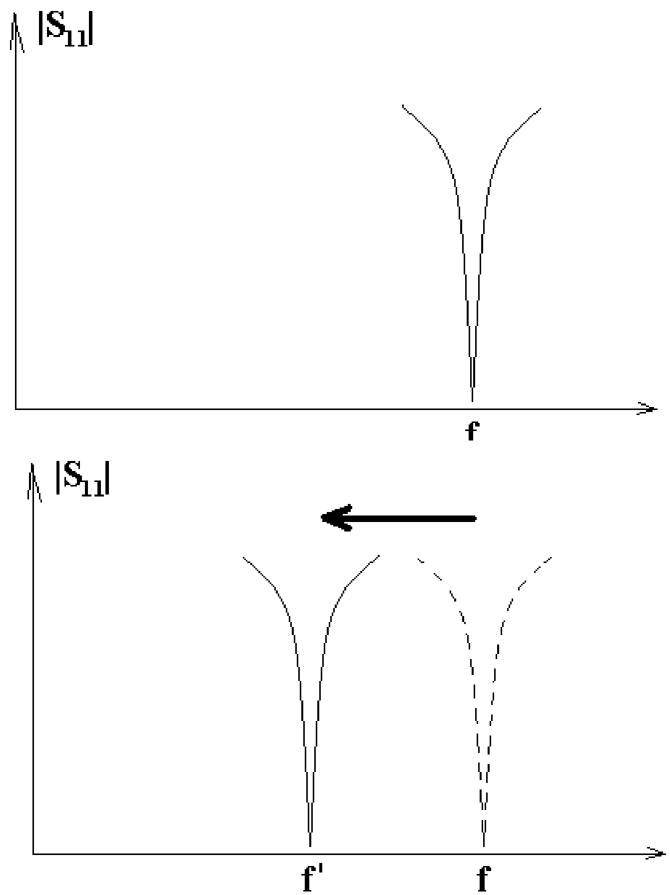
- Self actuation and sensing (with piezoelectric ZnO or AlN)
- Film bulk acoustic resonator (FBAR)
  - More than 100 million FBARs per year produced in 6” CMOS fabs

FBAR as a Mass Sensor

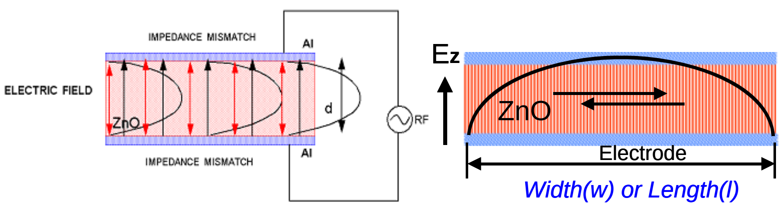
❖**FBAR consists of a deposited piezoelectric film, two metal electrodes and a supporting diaphragm (optional).**

- its resonant frequency of ~GHz is determined by the thickness of its layers
- the resonant frequency decreases with any mass added to its surface.

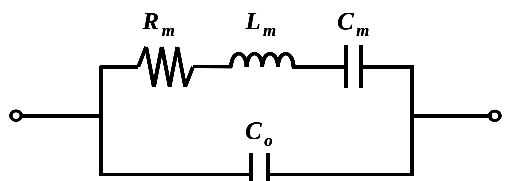




MEMS Resonator Characteristics (Piezoelectric vs. Electrostatic)



Piezoelectric



❑ Electromechanical coupling coefficient

$$k_t^2 = \frac{e_{33}^2}{e_{33}^2 + c_{33}^E \cdot \varepsilon_{33}^S}$$

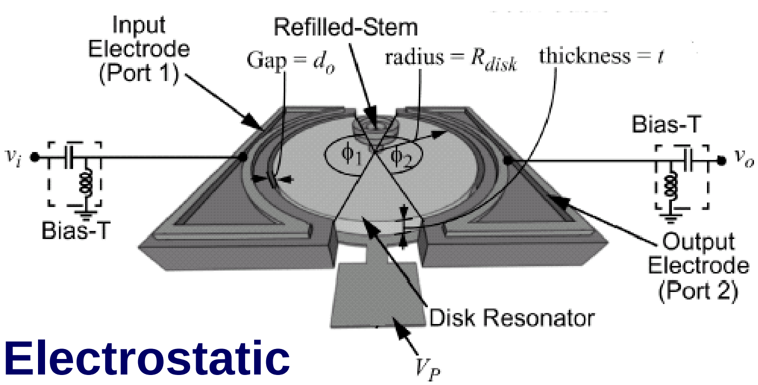
Material dependent, and more than 1%

❑ Input impedance (motional resistance R_m)

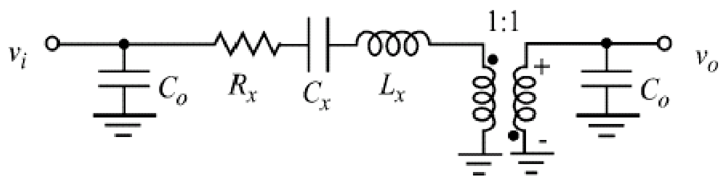
$$R_m \propto$$

$$\frac{1}{f_r \cdot Q}, \frac{1}{k_t^2}, d \text{ or } w, \frac{1}{A_{electrode}}$$

Easily matched to 50Ω



Electrostatic



$$\eta \propto$$

$$V_{DC}, \kappa, V_a, \frac{1}{f_r}, \frac{1}{d_0^2}, t$$

Typically less than 0.001%

$$R_x \propto$$

$$f_r, \frac{1}{Q}, m_{re}, \frac{1}{\eta^2}$$

Typically more than 50 kΩ

Minimum Detectable Mass (MDM)

$$\delta m \approx \boxed{\frac{\delta f_0}{f_0}} \boxed{m_{eff}}$$

Resonator Mass

Noise Floor

- Minimum detectable mass (MDM) is determined by
  - resonator frequency fluctuation (thermo-mechanical noise) ⟸ Q factor
  - resonator mass
  - noise of detection circuit
- Nano-scale resonator has low mass, but also has low Q in air

Mass Sensitivity in cm²/g

❖Mass sensitivity defined as resonant frequency change ($\Delta f/f$) per added mass ($\Delta m'$ in g/cm²) is

$$S_m = \lim_{\Delta m \to 0} \left(\frac{\Delta f}{f} \right) \left(\frac{1}{\Delta m'} \right)$$

$$= -\frac{1}{\rho_0 d} \quad \text{or} \quad -\frac{1}{\rho_0 w}$$

$$= -726\ \mathrm{cm^2/g} \quad \text{for 1.4 GHz FBAR Mass Sensor}$$

$$= -44\ \mathrm{cm^2/g} \quad \text{for 60 MHz LEM Mass Sensor}$$

$$= -14\ \mathrm{cm^2/g} \quad \text{for 6 MHz Quartz Crystal Microbalance (QCM)}$$

❖This sensitivity in cm²/g is to be used for mass sensors detecting mass concentration (e.g., g/cc) in sensing environment.

❖For detecting absolute mass quantity (e.g., g) brought to mass senor, the sensitivity in g/Hz is a better barometer for intrinsic sensing capability.

Mass Sensitivity in g/Hz

$$S_m = \frac{\delta m}{\delta f} = \frac{m_{eff}}{f_0}$$

The smaller, the better.

❑LEM piezoelectric resonant sensor

$$S_m = \frac{\delta m}{\delta f} \approx 2\frac{\rho}{V_a} w^2 l d$$

❑FBAR mass sensor

$$S_m = \frac{\delta m}{\delta f} \approx 2\frac{\rho}{V_a} w l d^2$$

l: length of resonator
w: width of resonator
d: thickness of resonator
ρ: density
V_a: acoustic velocity

❑LEM and FBAR sensors have comparable mass sensitivity with NEMS sensor when the lateral dimensions (e.g., *w* and *l*) are reduced.

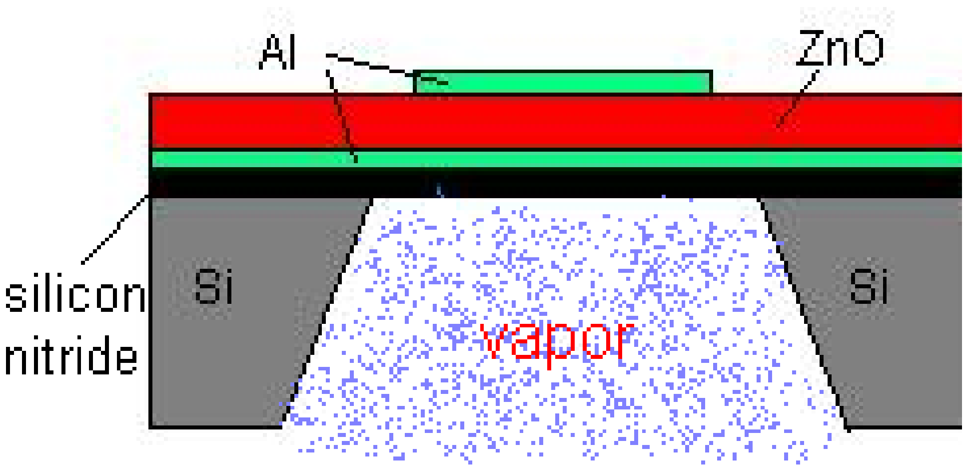
❑NEMS cantilever mass sensor

$$S_m = \frac{\delta m}{\delta f} \approx \pi \frac{\rho}{V_a} l^3 w$$

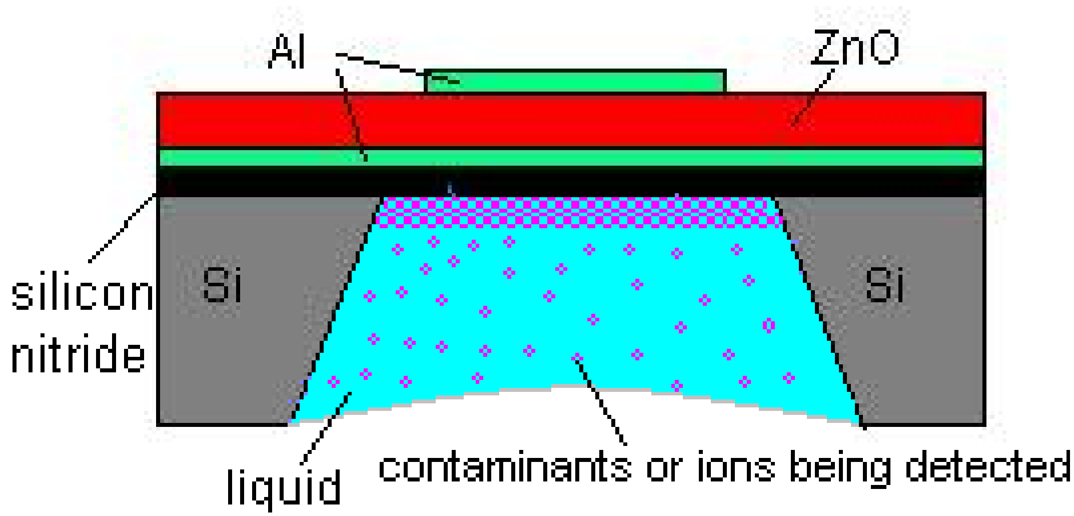
l: length of cantilever
w: width of cantilever

S_m of ~10^{-18} g/Hz is obtained with a NEMS sensor having *l* = 2μm and *w* = 2μm.

FBAR Mass Sensor



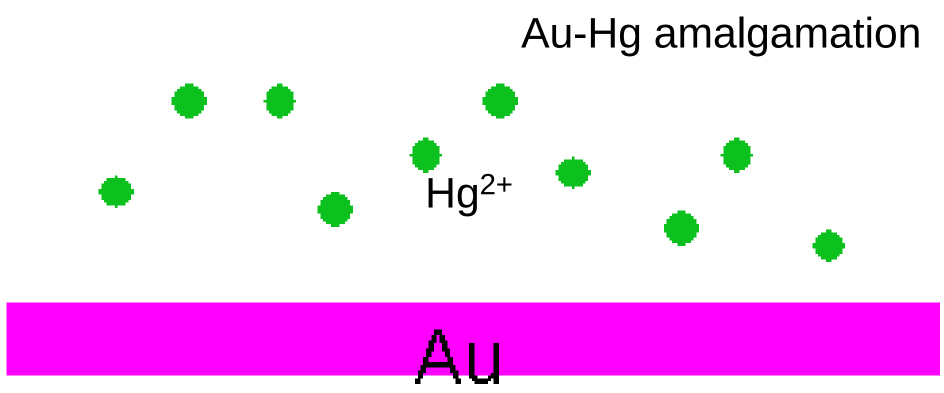
Vapor Mass Sensing

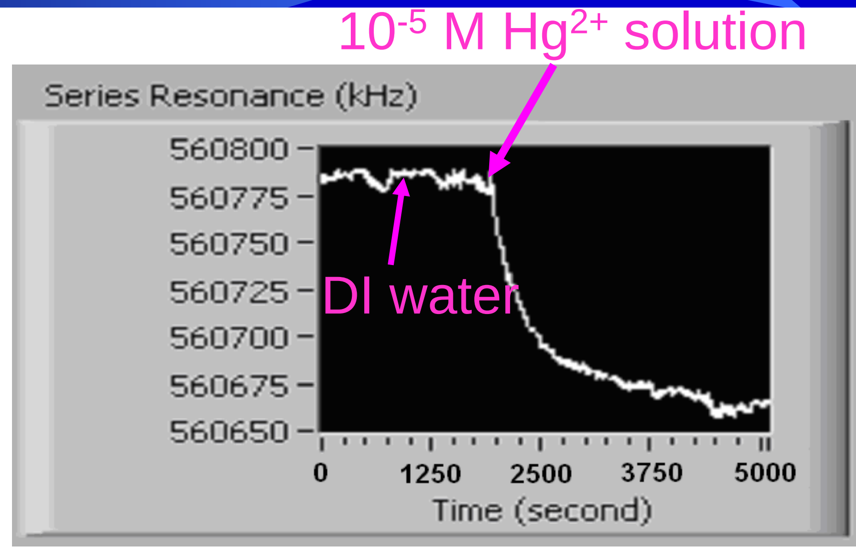


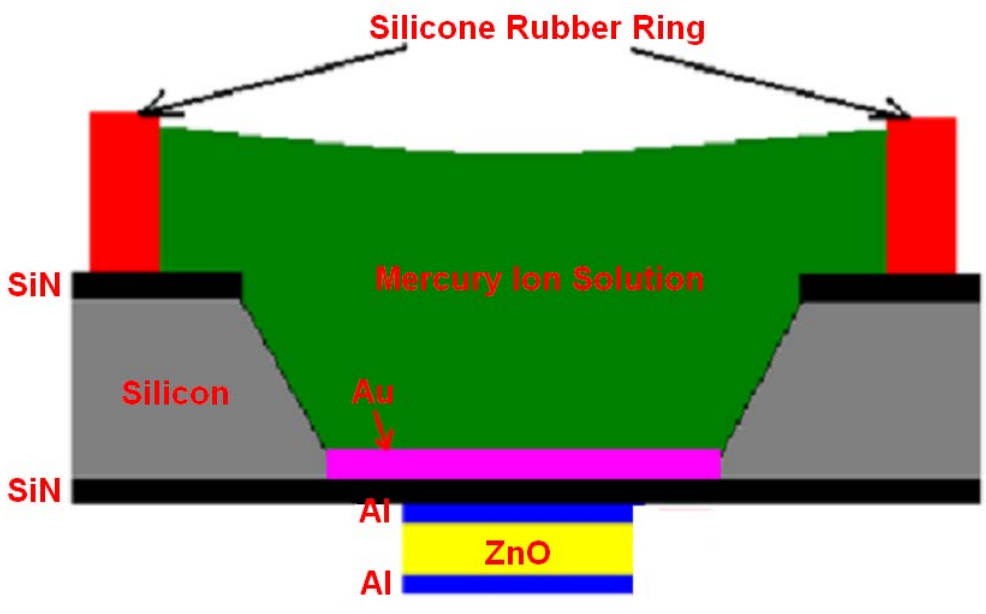
Mass Sensing in Liquid

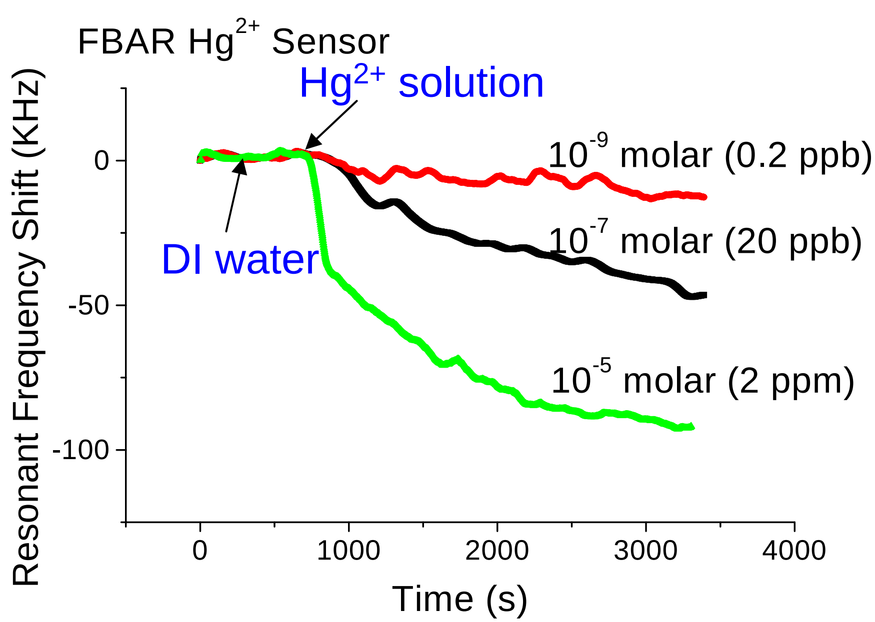
- Easy packaging, array formation and impedance matching to 50Ω.
- Small size (100 μm ×100 μm×2 μm)
- Operational in air and water.
- High mass sensitivity.
  - 10^{-18} g/Hz with small FBAR (10 μm×10 μm×2 μm).

Measured FBAR Response in Hg^{2+} Solution

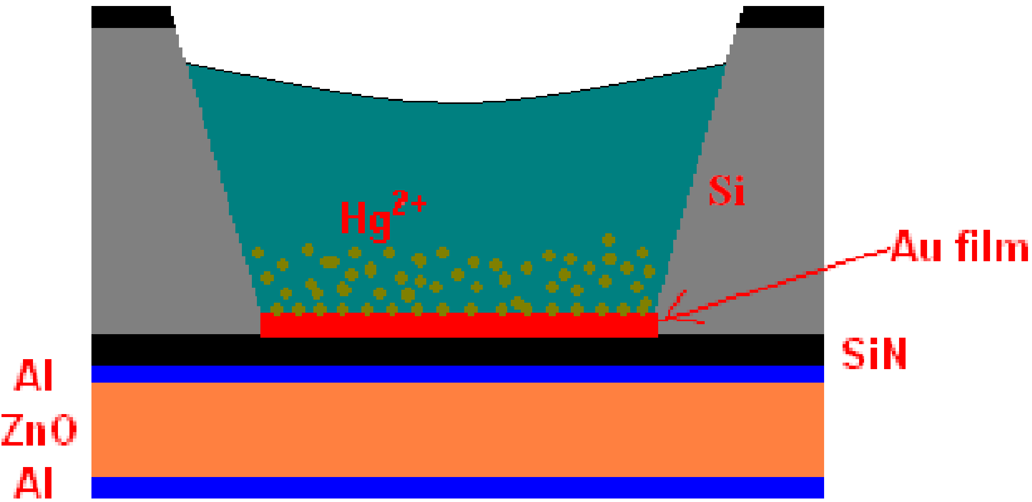


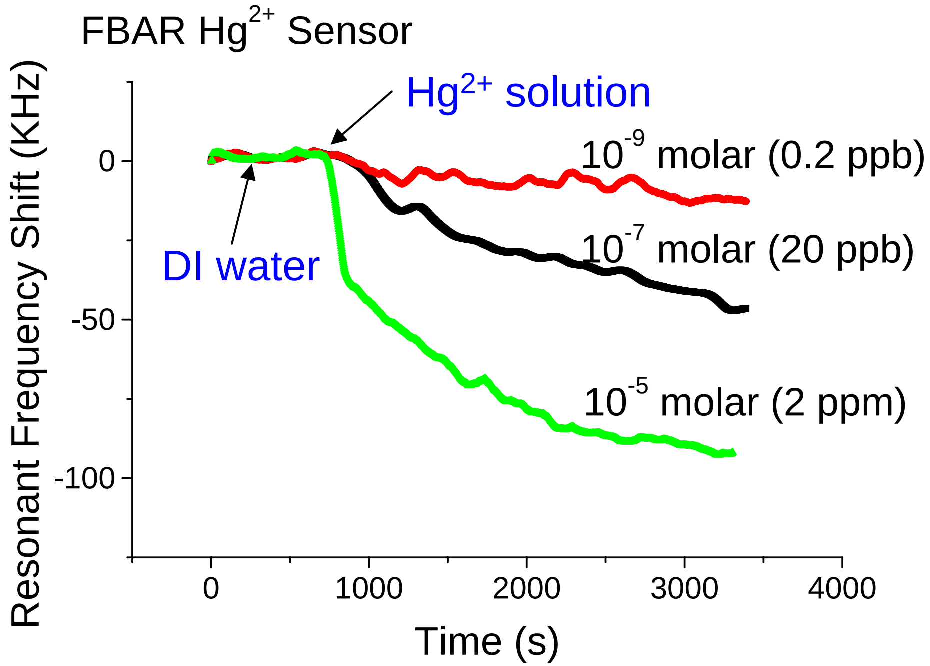






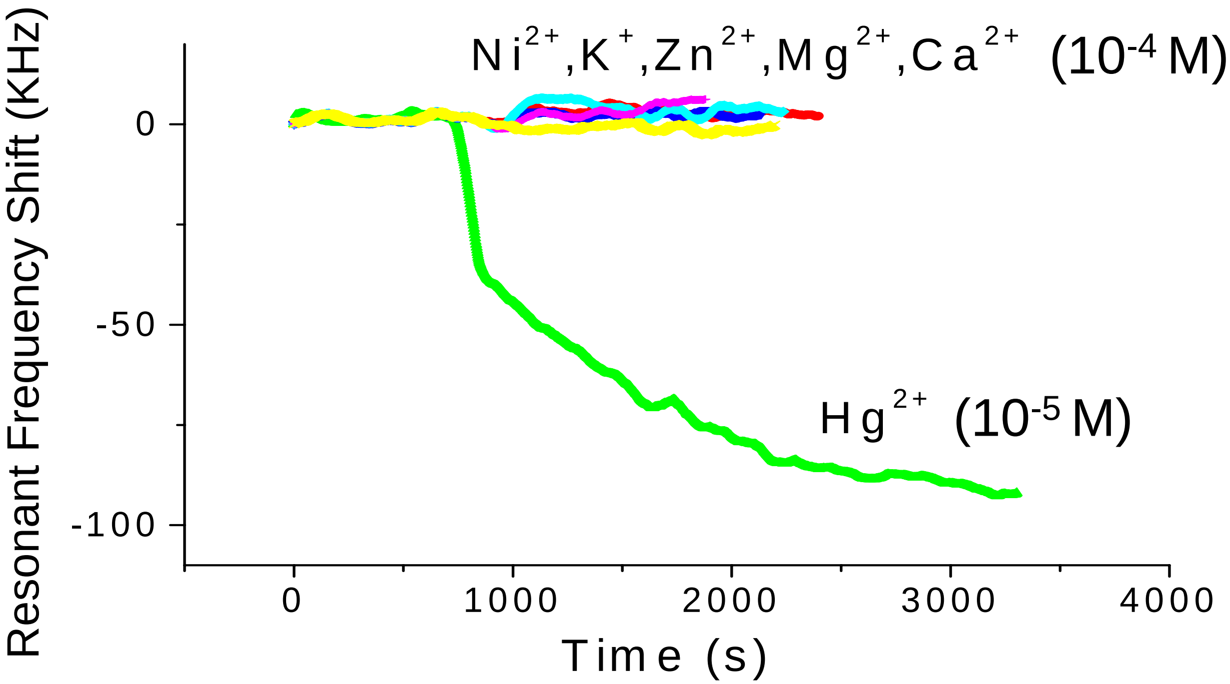
Measured Mercury Ion Sensing by FBAR





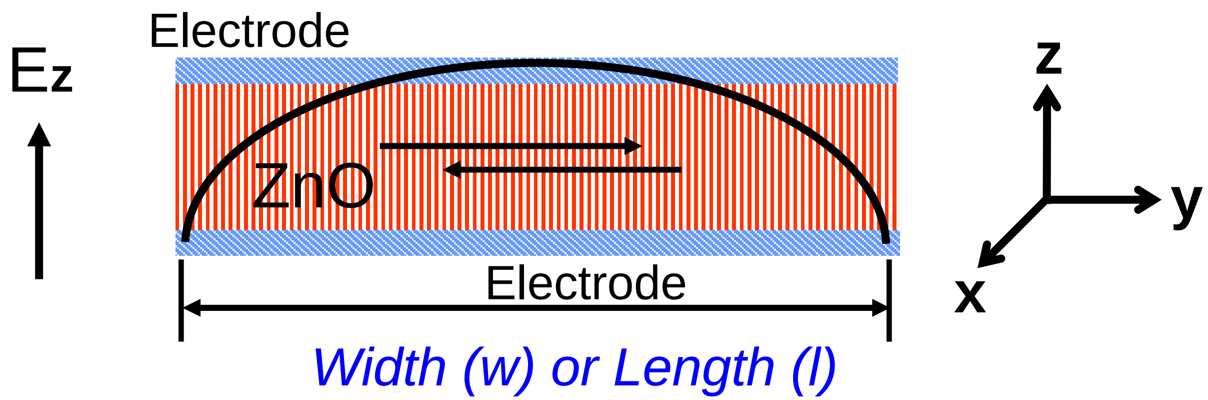
- Detection limit: ~ 10^{-9} M Hg^{2+} (0.2 ppb)
  - According to the Environmental Protection Agency (EPA), drinking water should have Hg^{2+} concentration no higher than 2 ppb.
- The sensor can be re-usable, since
  - the mercury ion can be released from the gold layer by brief heating or by 24 hour incubation at room temperature in a mercury-free atmosphere *[McNerny J J, Buseck P R and Hanson R C 1972 Science* ***178,*** *611].*

Selectivity of the FBAR Mercury Sensor



- The selectivity of the Au-coated FBAR sensor for Hg^{2+} over other cations such as K^{+}, Ca^{2+}, Mg^{2+}, Zn^{2+}, Ni^{2+} is measured to be extremely good.
- None of the cations (all with a concentration of 10^{-4} M) can produce any significant frequency shift, while the FBAR resonant frequency changes around 90 kHz for 10^{-5} M Hg^{2+}

Lateral Extensional Mode (LEM) Piezoelectric Resonator



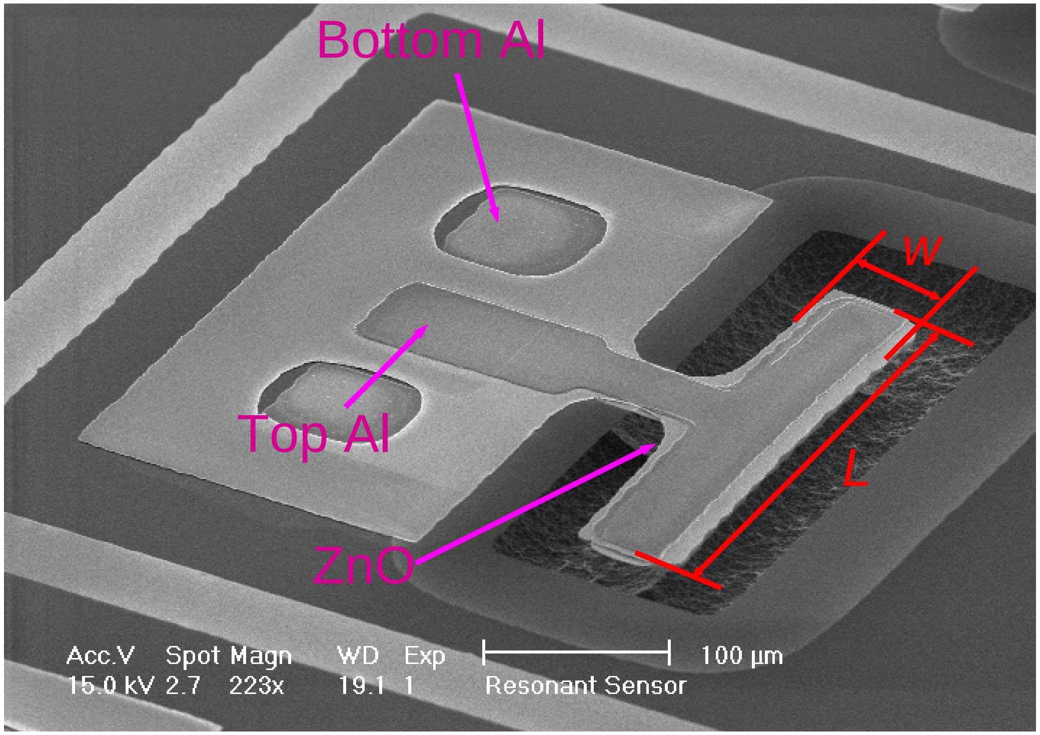
$$\begin{bmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{31} \\ 0 & 0 & e_{33} \\ 0 & e_{15} & 0 \\ e_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_x = 0 \\ E_y = 0 \\ E_z \neq 0 \end{bmatrix} = \begin{bmatrix} T_x \neq 0 \\ T_y \neq 0 \\ T_z \neq 0 \\ T_{xy} = 0 \\ T_{yz} = 0 \\ T_{xz} = 0 \end{bmatrix}$$

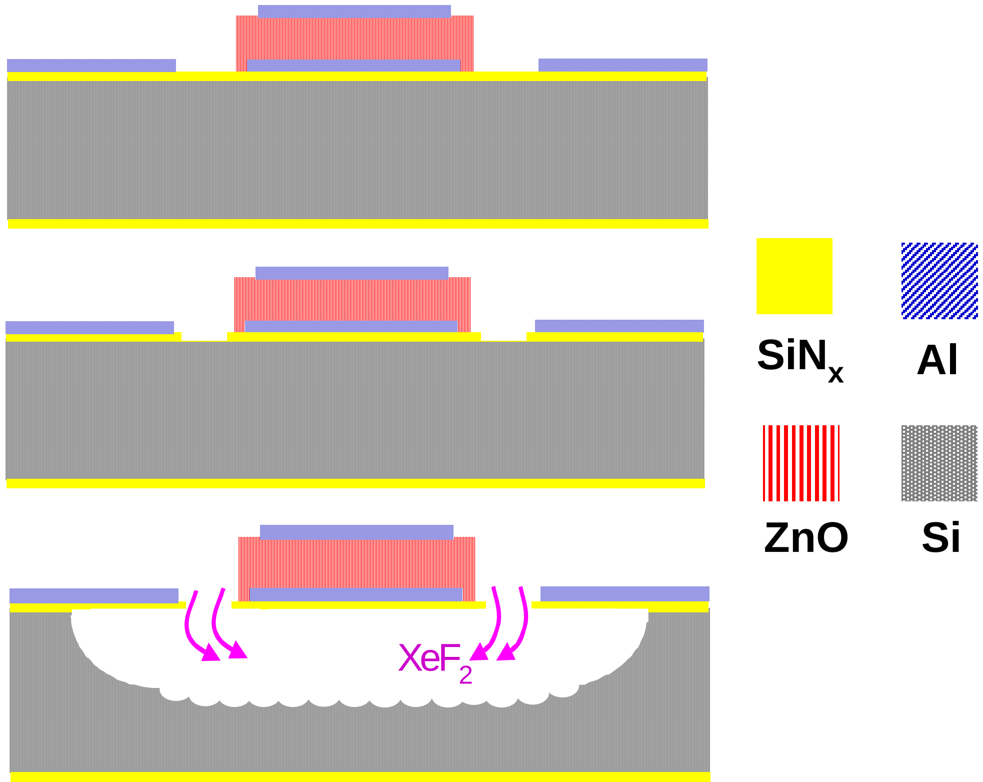
- Acoustic waves generated by none-zero in-plane stress (T_x or T_y).
- Resonant characteristics (e.g., $f=V/2w, Z_{in}$) are determined by the width and length.

$$k_t^2 = \frac{K^2}{1+K^2} \quad V_a = \sqrt{\frac{C_{11}^E}{\rho}(1+K^2)} \quad K^2 = \frac{e_{13}^2}{c_{11}^E \cdot \varepsilon_{33}^S}$$

$k^2_t \sim 1.7\%$ $V_a \sim 6100 m/s$

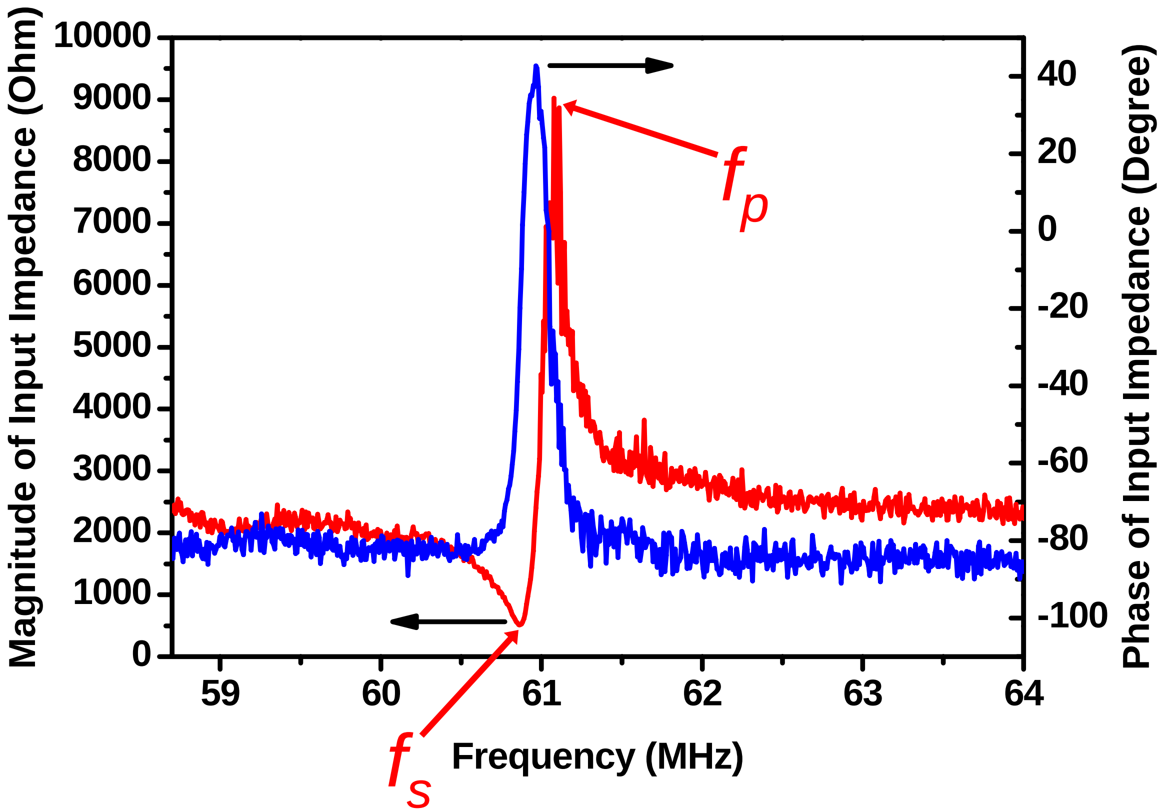
Fabrication of LEM Piezoelectric Resonator





- XeF_2 dry release with silicon as a sacrificial layer
  - CMOS compatible.
- Resonant frequency is photolithographically definable.
- Impedance could be decreased by increasing the length (*L*).

Measured Characteristics of LEM Piezoelectric Resonator



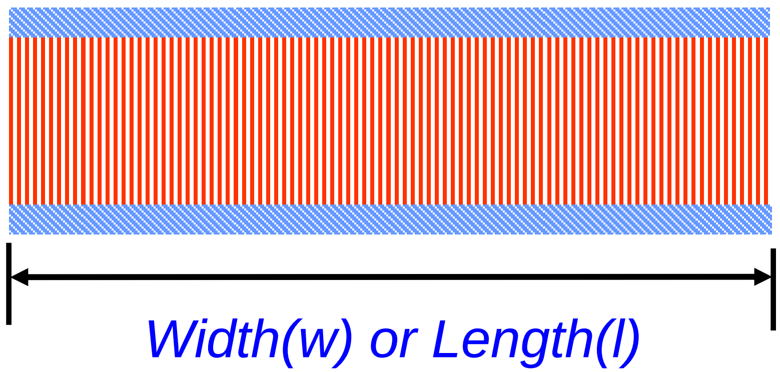
$$k_t^2 \approx \frac{\pi^2 (f_p - f_s)}{4 f_s} \approx 1.1\%$$

$$Q = \frac{f}{2} \frac{d\phi}{df} \approx 1{,}406$$

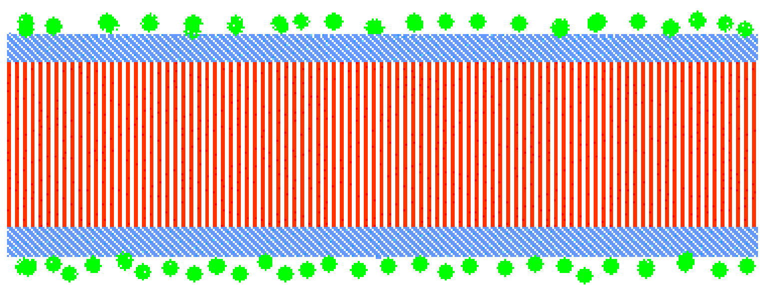
in air

- Relatively high electro-mechanical coupling coefficient and Q
- Q is mainly determined by internal material property
  - Q of flexurally vibrating resonator is determined by viscous damping of air
- About 500 Ω impedance at f_s (≈61 MHz).
  - can be decreased by increasing the length (L).

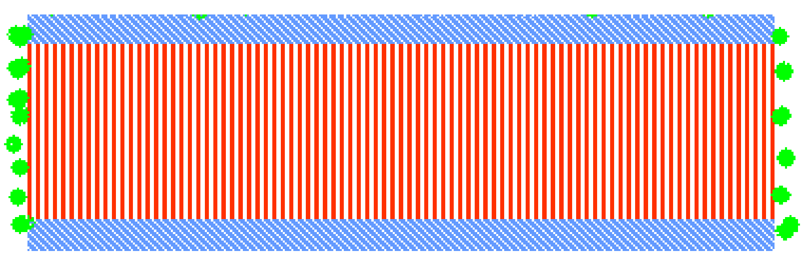
Resonant Frequency Shift Due to Mass Loading



- **Resonance frequency (f_0) is determined by lateral dimension (*width or length*), not thickness (*d*).**

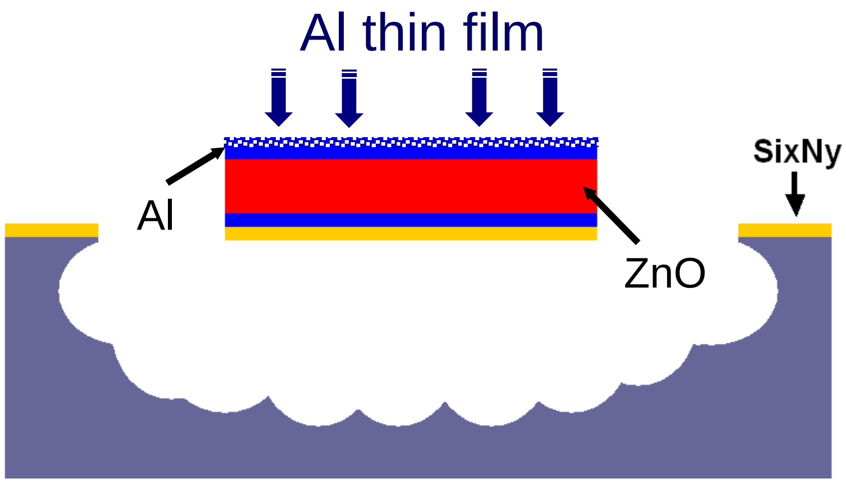


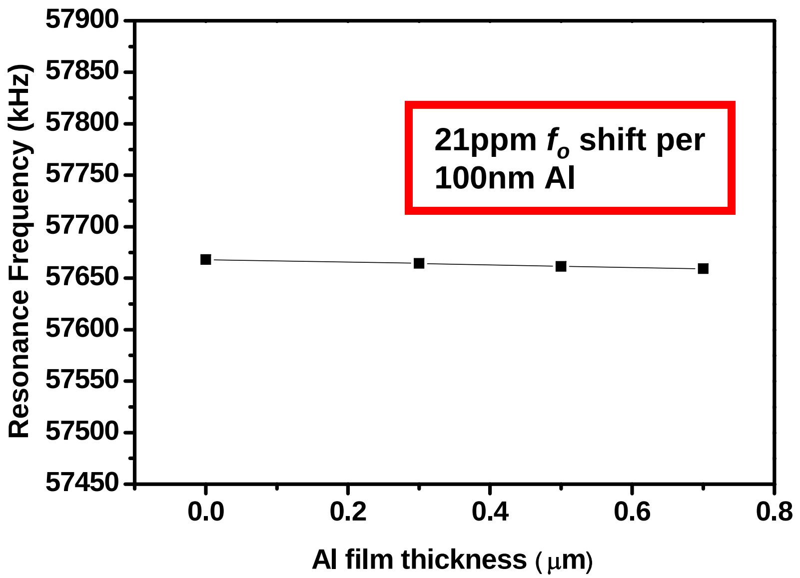
- **The mass added on the top or bottom surface has little effect on the resonant frequency.**

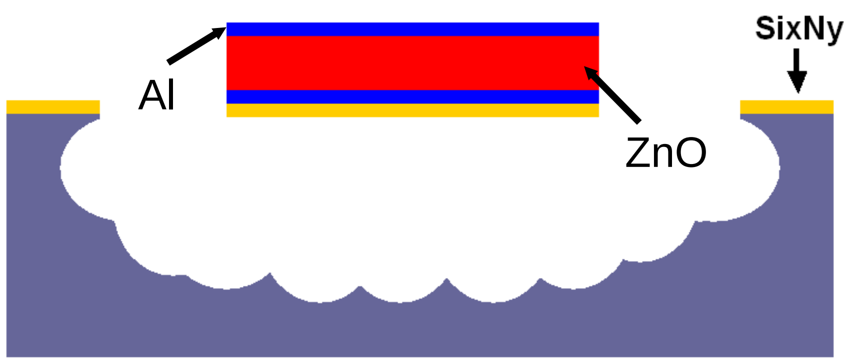


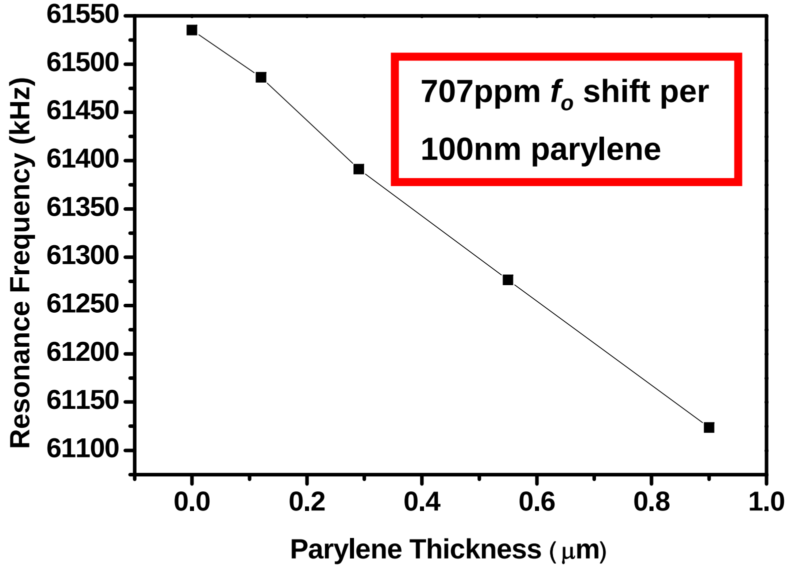
- **The mass added on the sidewalls has pronounced effect on the resonant frequency.**

Measured Resonant Frequency Shift Due to Mass Loading









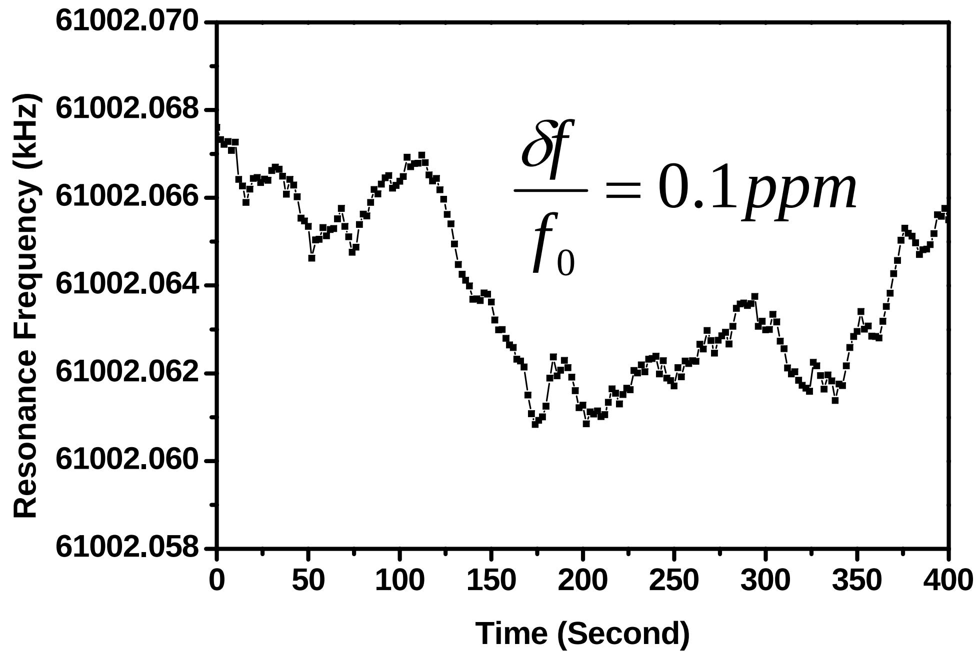
Minimum Detectable Mass and Mass sensitivity

- When mass change is much smaller than the mass of the resonator itself:

0.2μm Si_xN_y / 0.1μm Al / 0.6μm ZnO / 0.1μm Al

200μm×50 μm×1μm

$$\delta m \approx \frac{\delta f}{f_0} m_{total}$$



- 0.1ppm noise floor corresponds to a minimum detectable mass change of **4.6×10^{-15}g** on the resonator's sidewall.

- Mass sensitivity:

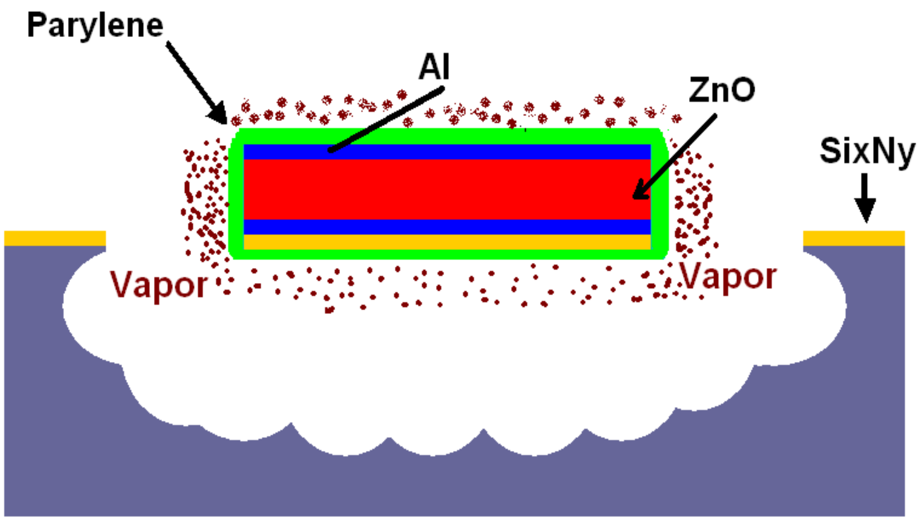
$$S_m = \lim_{\Delta m \to 0}\left(\frac{\Delta f}{f}\right)\left(\frac{1}{\Delta m'}\right) = -\frac{1}{\rho_0 w} = 44.48\ \text{cm}^2/\text{g}$$

$$S_m' = \frac{\delta m}{\delta f} = \frac{m_{eff}}{f_0} \approx \frac{4.6\times10^{-8}}{60\times10^6} = 7.7\times10^{-16}\ g/Hz$$

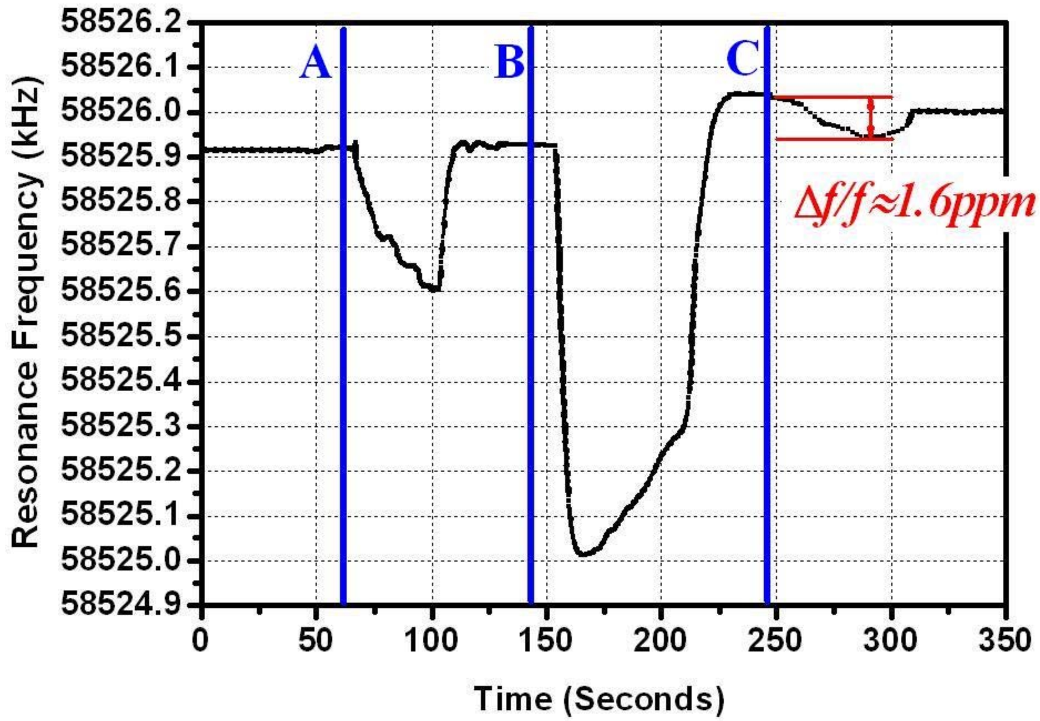
- 0.1 ppm noise is dominated by resonator's sensitivity to temp. fluctuation
  - Resonator TCF: ~-40 ppm/ºC

ρ_{Al}=2.7g/cm³, ρ_{ZnO}=5.68g/cm³,
ρ_{SixNy}=2.85g/cm³, $\rho_{parylene}$=1.35g/cm³

Isopropanol Vapor Detection in Air



Measured Response of the LEM Resonator Coated with Parylene.



- The A, B and C are time points when different amounts of IPA are added.
- Minimum detectable frequency shift of ~1.6ppm corresponds to an added mass of about **73fg**.

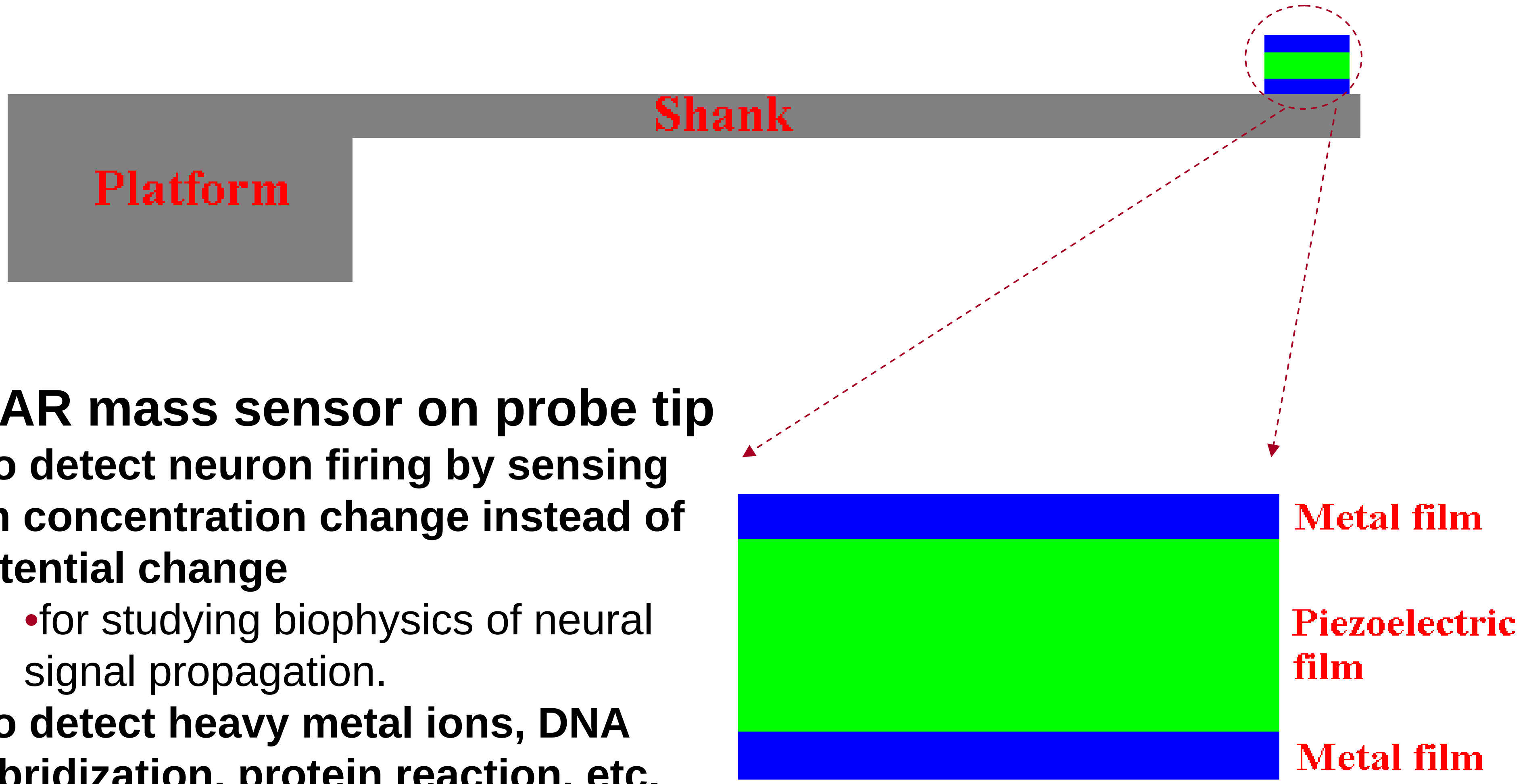
$$\delta m \approx \frac{\delta f}{f_0} m_{total}$$

LEM Sensor in Comparison with Other Resonant Mass Sensors in Air

Resonant Mass Sensor		Device dimension $w \times l \times t$ (μm^3)	Operating frequency	Q factor		Minimum detectable mass (MDM) in air
				In air	in water	
LEM piezoelectric resonator		200×50×1	60MHz	1400	64	73 fg
FBAR		200×200×1.5	1.5GHz	~250	40	~1300 fg
Flexurally vibrating cantilever	laser detection	2×6×0.7	2.2MHz	25	N.A.	5.5 fg
	capacitive sensing	20×0.425×0.6	1.45MHz	70	N.A.	57 fg

- LEM piezoelectric resonant sensor
  - femtogram mass detection in air, at room temperature.
  - portability, low power consumption.
  - MDM is expected to be 1,000 times better by shrinking the size.
    - real-time detection of molecules without vacuum.

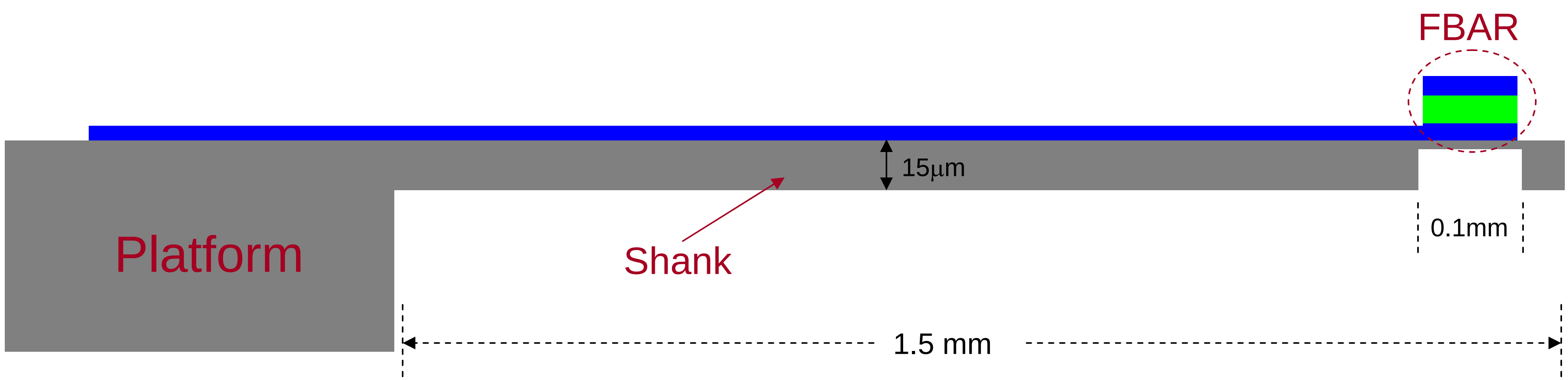
Microprobe with Resonant Mass Sensor



- **FBAR mass sensor on probe tip**
  - **to detect neuron firing by sensing ion concentration change instead of potential change**
    - for studying biophysics of neural signal propagation.
  - **to detect heavy metal ions, DNA hybridization, protein reaction, etc.**

Film-Bulk-Acoustic-Resonator (FBAR)

FBAR on Micromachined Probe



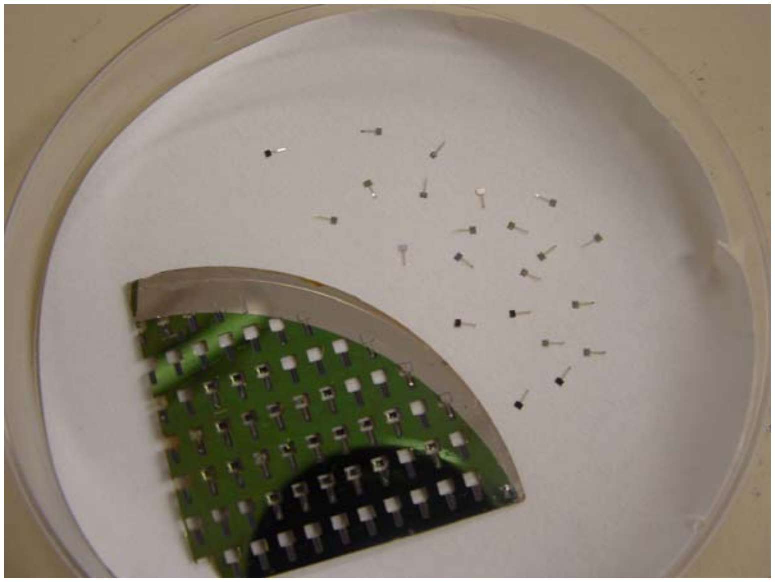
❖ **FBAR's size minimized to be placed at proble tip.**

❖ **Support layer under FBAR must be thin for high Q.**

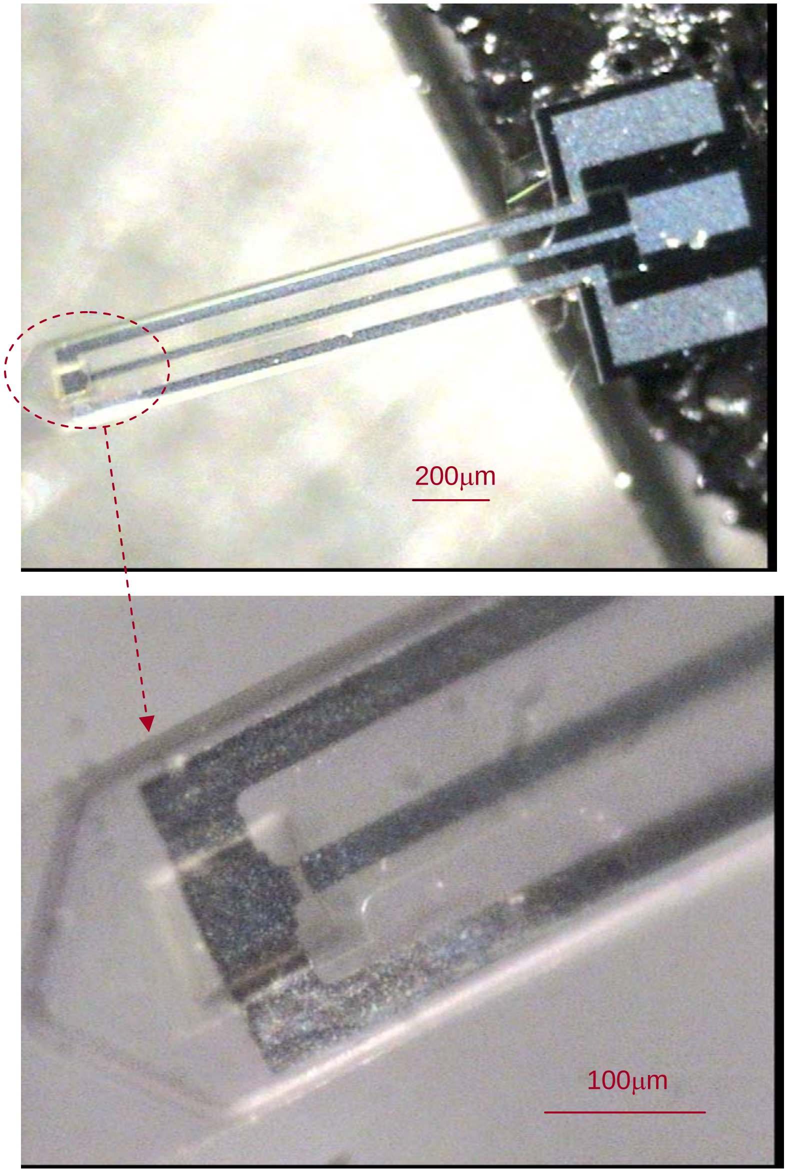
❖ **Long leading electrode from FBAR to platform requires shank with low RF loss**

- ➢ SU-8 for the shank
  - Much lower RF loss than silicon
  - Flexible and sturdy

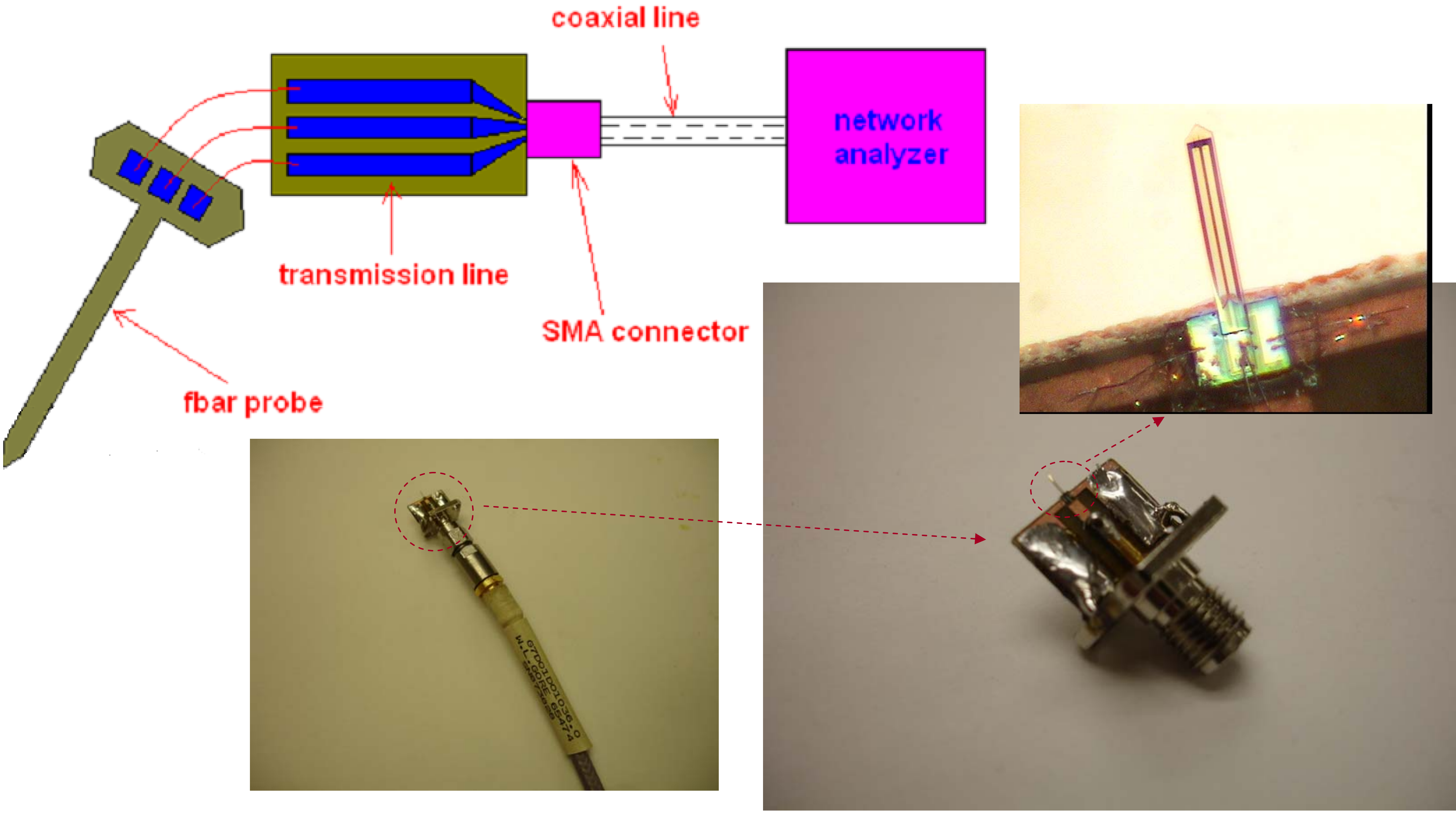
Pictures of Released SU-8 Probes



forced to bend by about 70º



SU-8 Probe Wire-bonded to Copper Transmission Line



Summary

- **3.68 GHz oscillator based on HBAR having a loaded Q of 19,000**
  - phase noise: -102dBc/Hz @10kHz offset
  - 3.2 mW power consumption.
  - Allan deviation: 1.5×10^{-9} @ 1 sec for a free-running oscillator.
- **Single-mode HBAR with Q of 7,300 at 3.13 GHz**
  - integrated with FBAR filter on a single chip $0.8 \times 0.4 \times 0.4 mm^3$.
- **Temperature-compensated HBAR**
  - total frequency shift of 8.16ppm from 60 to 90°C.

- **1.4 GHz FBAR's mass sensitivity of 726 cm^2/g**
  - minimum detectable mass density of 1 ng/cm^2 in air where the Q is 250.
- **60 MHz LEM resonator**
  - 4.6 fg minimum detectable mass
  - measured 73 fg isopropanol vapor detection
- **Attogram mass detection by scaling down the size to submicron scale.**
- **Hg^{2+} sensing by FBAR based sensor**
  - 0.2 ppb minimum detection with FBAR having Q of 400.
- **Micromachined SU-8 probe with an integrated FBAR sensor at its tip**